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The Pre-Blast Concept for use on Armour Materials

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ABSTRACT

It can sometimes be difficult to determine whether vehicles damaged by blast loading are repairable in theatre or so significantly damaged that the hulls must be scrapped. The primary purpose of this investigation is to provide basic metallurgical data to assist in determining the criteria of failure. On top of this, it may be possible that blast loading may actually improve the performance of vehicles by work hardening of the hull and it might be possible to use controlled blasting as a technique to improve blast resistance

Repeated blast test results (up to 7 times) of candidate armour materials showed that the greatest deformation occurred during the first blast and subsequent blasts showed less evidence of deformation. This demonstrates that the steel experienced a significant increase of work hardening after the first blast, at which stage the steels reached a saturated level. Despite repeated blasting, there was little evidence of cracking in the armour steels and Crack-starter explosion bulge testing of the armour steels at -18 ^{o}C demonstrated that the steels have adequate toughness in the as-welded condition. This indicates that blasting is not detrimental to the subsequent blast performance of armour.
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The work also suggests that appropriate blasting may have a work hardening effect that may be used to increase blast resistance of steels. To test this, the 'pre-blast' concept test program includes hardening of materials by sheet charge blast loading and subsequent testing of steels by multiple explosion bulge testing. Steels investigated include TWIP steels, a wear plate and armour steels with hardness 450 HV or higher (up to 650 HV). In general, the improvement in deformation resistance is associated with increases in hardness combined with reductions in microstructural grain size.

In practical terms, this work demonstrates that vehicles subjected to blast damage in theatre should not be condemned on the sole assumption that metallurgical damage has occurred to the armour material. Significant savings in cost of repair to blast damaged vehicles could be achievable and vehicle availability could be increased considerably.

The Pre-Blast Concept for use on Armour Materials

Executive Summary

It can sometimes be difficult to determine whether vehicles damaged by blast loading are repairable in theatre or so significantly damaged that the hulls must be scrapped. The primary purpose of this investigation is to provide basic metallurgical data to assist in determining the criteria of failure. The secondary goal of this work is to investigate the possibility that blast loading may actually improve the blast performance of armour materials. It is possible that blast loading may actually improve the performance of vehicles by work hardening of the hull and it might be possible to use controlled blasting as a technique to improve blast resistance

Repeated Explosion Bulge blast testing (up to 7 times) of candidate armour materials showed that the greatest deformation occurred during the first blast and subsequent blasts showed less evidence of deformation. This demonstrates that the steel experienced a significant increase of work hardening after the first blast, at which stage the steels reached a saturated level. Despite repeated blasting, there was little evidence of cracking in the armour steels and Crack-starter explosion bulge testing of the armour steels at -18 ºC demonstrated that the steels have adequate toughness in the as-welded condition. This indicates that blasting is not detrimental to the subsequent blast performance of armour.

One likely effect of blast loading of armour steel is the reduction in microstructural grain size and it is well known that steels with ultra-fine grains (UFG) produce outstanding high strength and toughness. These properties should improve the performance of the armour. However, owing to the complicated microstructures of armours, the effect of blasting on grain size and the effect of grain size on the improvement of strength and toughness is not entirely clear.

In this paper, a possible technique to obtain UFG in armour materials is proposed. The pre-explosion concept is presented as a means of improving strength and toughness through refining the grain size.

The test involves hardening of materials by sheet charge blast loading. Steels investigated include TWIP steels, a wear plate and armour steels with hardness 450 HV or higher (up to 650 HV).

Microstructural analysis showed that there are trends that, with increasing loads, the mid-section grain sizes decrease or stay at the before-blast level, but grain sizes close to the surface increase or stay the same. Pre-saturated soft materials with high elongation such as TWIP steel have a high possibility to improve the strength with minor loss of toughness.

In practical terms, this work demonstrates that vehicles subjected to blast damage in theatre should not be condemned on the sole assumption that metallurgical damage has occurred to the armour material. Significant savings in cost of repair to blast damaged vehicles could be achievable and vehicle availability could be increased considerably.

Authors

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Chang Choi obtained a Master's degree in Materials Science at the University of Oregon and undertook PhD study at the University of Illinois and later at the University of New South Wales, where he received a PhD with a thesis on superconductors. He has been employed as a materials scientist at DST Group Maritime Platforms Division since 1998. During the period 1998 to 2006, he worked with the metallurgy section. From 2006 to 2009, he worked in the biology section, from 2009 in the Armour Mechanics and Vehicle Survivability group and, most recently with IPP Group of Land Division.

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Brian Dixon is a Scientist in the Land Division of DST Group. He has been employed at DST Group since 1978, undertaking experimental development and fundamental studies into weld metal solidification cracking in steels and stainless steels. He has also undertaken extensive work on improving the weld zone toughness of high strength steels. During 1989 and 1990 Brian worked at Kockums Laboratory in Sweden as part of DST Group's contribution to the submarine project. Since 2001, Brian has worked in a number of developmental positions, including Director, Program Office (Maritime), STCC for M1 and M6 and S&T Adviser for JP 2048 and now Senior Research Fellow in Land Division.

Contents

1. Introduction

Vehicles subjected to blast loading in theatre may be declared inoperable due to metallurgical damage. It has been argued that the steel may undergo degradation in its mechanical properties or develop hazardous micro-cracks as a result of the blasting process and these defects would lead to premature failure if the hull was subjected to subsequent blast loading. Loss of a vehicle in service comes at great expense because the vehicle must be replaced. Furthermore, it creates a capability gap until the vehicle can be replaced.

The purpose of this investigation is to assess if any metallurgical damage has occurred as the result of blast loading. Information gained from this work will provide data to support the assessment of vehicles in theatre and may allow those vehicles that have sustained minor hull deformation to be returned to service.

One classical effect of working steel is the reduction in microstructural grain size. It is well known that material with ultra-fine grains (UFG) produce outstanding high strength and toughness. It might therefore be concluded that blast loading would actually improve the performance of armour, provided mechanical damage is contained and cracking is avoided. Unfortunately, owing to the complicated microstructures of these materials, the grain size effect on the improvement of strength and toughness is not entirely clear. [1-4].

Since the UFG concept was accepted as a valuable method to improve the strength and toughness of steels, various techniques were introduced to reduce the grain size. Accumulative roll bonding (ARB) as a form of Severe Plastic Deformation (SPD) was introduced by Seito et al [1], and it has been considered to be one of the optimistic methods to achieve UFG sheet metals [2-3]. However, SPD and its derivatives are very expensive and the amount of material produced is very limited owing to the shortage of press milling facilities.

Another possible technique is a pre-blast method which is described and investigated in this work. If SPD and ARB methods can both produce UFG, the pre-blast should also produce UFG by high instantaneous impact in at least one direction.

In the previous experiments [4], DST Group demonstrated that with single or repeated blasting, the work hardening of certain steels was significantly increased. In particular, pre-blasting of TWIP steel increased hardness owing to twinning effects by which the effective grain size was reduced dramatically [5].

In this paper, use of the pre-explosion technique to obtain UFG is investigated. The technique involves hardening of materials by sheet charge blast loading. Steels investigated include TWIP steels, a wear plate and armour steels with hardness 450 HV or higher (up to 650 HV).

2. Experimental

2.1 Explosive Test Setup

Testing is undertaken with the standard explosion bulge test [6]. The tests are performed by two different methods. One is to measure bulge depth with continuous blast up to 7 times by 2.3 kg PE4 charge (160 mm diameter cylindrical shape). All the materials are 'as received' without any pre-blast. The second technique is to do pre-blast with various sheet charge thicknesses and to subsequently test these steels by explosion bulge testing.

2.2 Metallography

Following explosive loading, metallographic specimen preparation was undertaken to examine the microstructural evolution through the plate thickness. Firstly, a section was wire-cut from the joined plates in order to investigate the cross-section. Grinding was then undertaken using 800 to 1200 grade SiC abrasive papers with water as a lubricant. This was followed by polishing with progressive diamond suspensions of 6 μm, 3 μm, and 1 μm using a water-based lubricant. The TRIP type steel and HARD steel microstructures were etched using 2% Nital followed by metallographic examination and photographic recording. The superaustenitic steel microstructures were revealed using an electrolytic etchant of 10 g oxalic acid dissolved in 100 ml distilled water, at 4V for between 1 to 3 minutes. Microstructural analyses of the interfaces were undertaken via optical microscopy. The hardness variation of each joint in the through plate thickness direction was also characterised using Vickers microhardness testing, using a 200g load (HV_{200g}) and a Leco microhardness indenter.

For the procedure of acquiring hardness values, total 7 readings were obtained from tests and the maximum/minimum numbers were omitted. The average of 5 remaining values along with standard deviation is giving in this study.

2.3 Electron Back Scattered Diffraction (EBSD)

The microstructure was also analyzed by the electron back scattered diffraction (EBSD) technique conducted on a JEOL JSM-7001F field emission gun (FEG) fitted with a Nordlys–II(S) camera and the EBSD software, AZtecHKL at 15 kV, ~3.3nA and 24 mm working distance. Post processing of the obtained data was statistically analysed by HKL Channel-5 software. For all EBSD maps, the black lines indicate high angle grain boundaries (HAGBs) with critical misorientation > 15^0 (the misorientation less than 2° were disregarded). In the case of TWIP steels, other than HAGBs, twin boundaries (TBs) were taken into account. First order twin boundaries (TBs) are defined as Σ3=60° <111>, shown in red lines, while second order TBs are Σ9=38.9° <101>, represented in blue lines, yielding tolerance limit of 6° for Σ3 and 2.4° for Σ9, respectively. The uncorrelated, the misorientation data between randomly chosen points in the data set, misorientation angle distribution is displayed. The (1 1 1) pole figure for TWIP steel (FCC crystal structure) is shown representatively, while (1 0 0) is chosen for Dual phase (DP), C4, and C8 which are BCC.

2.4 Blast Testing

For the first trial, toughness and deformation resistance of four commercial armour steels were evaluated. The toughness of the steel materials was measured using the Explosion Bulge Test (EBT) [7]. The EBT utilises a standard explosive loading rate that is similar to loading rates typically seen in military events and it applies a reproducible energy to the plate so that materials can be directly compared. The test configuration is shown in *Figure 1*. It comprises a donut shaped die block on which the test plate is placed. A cardboard box, with a depth chosen to achieve the specified 320 mm standoff distance, is tightly fitted over the plate. A 2.3 kg explosive charge is placed on the centre of the topside of the box, which has been diagonally cross-marked to identify the correct charge placement location.

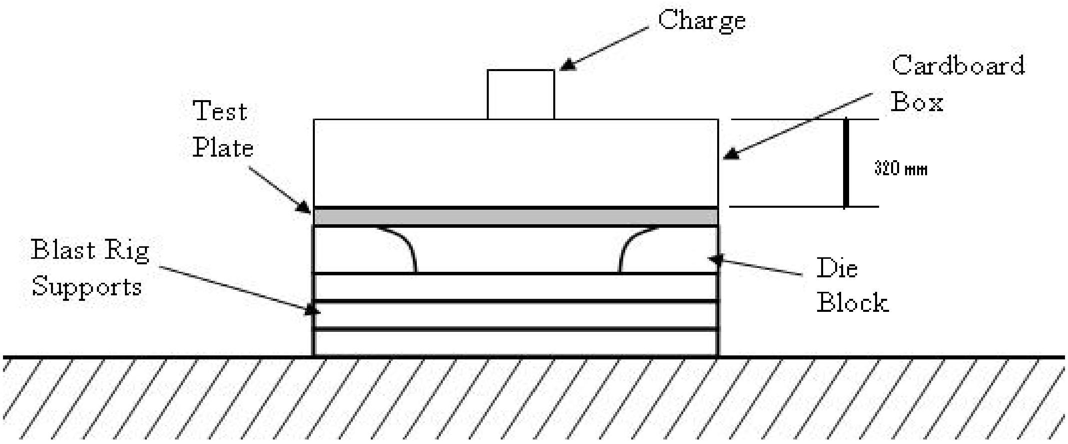


Figure 1: EBT configuration

In this work, the EBT was used to directly compare four commercially available armour steels, designated in this report as steels H, B, A and M. All steels underwent a quench and temper (Q&T) process using commercial processing technologies. However, it was noted that the metals possessed a range of chemistries and hardnesses and have different microstructures that can often give rise to performance variations under conditions of rapid loading [8].

To assess the materials for toughness, crack starter weld beads were deposited on the bottom centre of the test plates (B, H, M and A). These weld beads are composed of hard-facing material that is inherently brittle and, under blast loading, act as a 'crack starter' to force the initiation of brittle cracking in the weld zone and hence into the parent plate. After blasting, the depth of the bulge of the plate is measured to provide an indication of deformation resistance (elongation) and toughness of the steel is determined from the appearance of the fracture surface on any region of the plate that has fractured. The steel is subjected to multiple blasts in order to compare toughness and deformation performance. In addition to EBT results, the steels were compared using standard mechanical tests and metallographic inspection. Each of the steel plates was subjected to multiple explosive blasts, typically a maximum of seven blasts per test plate.

Before testing, each test plate was plasma-cut to dimensions of 760 mm x 760 mm to match the dimensions of the die block[1]. Two opposing corners of each plate were drilled through to clamp the plate with a bolted shackle. This was required to avoid the blasted plates impacting the ceiling of the blast chamber. A type ‘k’ thermocouple was then welded to a corner on the top side of the plates to monitor the temperature of the plate to ensure the correct test temperatures were achieved prior to testing.

EBT tests were carried out at approximately -18° C for each test plate. Images of the test plate, blast chamber, and a schematic of the test plate are shown in Figure 2, identifying the location of the crack starter weld, blast chamber, thermocouple, and clamp positions.

The stand-off distance for the plates with weld bead starter was 320 mm in all cases. 2.3 kg PE4 explosive charges were used for all test plates. The PE4 was packed into 160 mm diameter cylinders, which were made of cardboard.

Finally, the top and bottom sides of each test plate were wrapped with cardboard to insulate the plate so that its temperature did not increase rapidly while transporting the plate from the temperature conditioning chamber to the blast chamber and while warming the plate to the correct test temperature (-18° C). To achieve the testing temperatures the plates were placed in the temperature conditioning chamber at approximately -40° C and left to equilibrate overnight before testing.

Immediately prior to each test, the plate was removed from the conditioning chamber and placed on the die block. The thermocouple was then connected to a DT500 series ‘datalogger’ device to monitor plate temperature. The charge was detonated when the test plate had warmed to the required test temperature. Bulge depth measurements and macro images of the region adjacent to the hard-facing weld bead were taken after testing.

Table 1: Compositions and thicknesses of the steels under investigation

Steel	Thickness* (mm)	C	P	Mn	Si	Ni	Cr	Mo	Cu	S	Al
B	15.5	0.17	0.014	1.09	0.20	-	-	0.20	0.013	0.005	0.027
H	15.5	0.29	0.013	0.30	0.30	0.19	0.99	0.25	0.012	0.005	0.035
A	15.5	0.21	0.01	1.2	0.3	2.5	1.0	1.2		0.010	
M	15.5	0.22	<0.15	1.5	0.5	2.0	1.0	0.6		<0.005	

*nominal thickness

[1] The dimension from the top of the die block to the bottom of the blast rig supports is 250 mm.

Table 2: Mechanical properties of the steels under investigation

Steel	Hardness (H_B)	UTS* (MPa)	CVN* (J @ -40° C)	Elongation* (%)
B	255	790	40	18
H	350	1140	22	16
A	440	1450	35	12
M	440	1450	48	13

*average values

2.5 Pre-blast Trial

The materials in use were strengthened by pre-blast method in which a dedicated sheet charge was contacted over the plate to be tested. The thicknesses of the sheet charge varied from 2 mm to 8 mm. Four different steps of materials with different sheet charge were analysed by the pre-blast method (ie, as received, 2 mm, 4 mm, 6 mm and 8 mm)
Two letter/digit of detonation of the materials are adopted throughout this study. The first letter/digit is T, D, 4, and 8 representing TWIP, C Dual Phase (CD), C4 and C8, respectively. The second digit 0, 2, 4 and 6 mean as received without pre-blast, 2 mm, 4 mm and 6 mm sheet charge blasts, respectively. For example, sample ID 44 indicates 4mm sheet charge blast of C4 steel.

In the report, the toughness and deformation resistance of 3 commercial hard steels and commercial tough TW steel are evaluated to study the effects of pre-blasting.
PRIMA 1000 Sheet charge with 1.44 g/cc density and 7100 m/s detonation velocity was applied for this test. *Table 3* shows the details of the mechanical and the chemical properties of each plate in use for this second trial.

Table 3: the mechanical and the chemical properties of the steel

ID	Density	Typical	El.	KCVL	KCV (-40C)	Chemical	Composition													
	kg/dm^3)	Hardness (HB)	(%)	J/cm^2	J	C	S	P	Mn	Ni	Cr	Mo	Ti	SI	N	Cu	W	V	B	AL
C4	7.85	370	12	45(-4F)		<0.20	<0.005	<0.018	<1.60	~0.20	<1.90	<0.40	<0.20							
C8	7.85	470	12	55(-4F)		<0.28	<0.002		<1.60	<0.40	<1.60	>0.2								
CD	7.857	480	10	168 (-4F)		0.03	0.015	0.045	1.3	0.45	0.7	0.34	0.6							
M1	7.85	352-388			>20	<0.3	<0.005	<0.012	<1.20	<1.8	<1.5	<0.6		<0.4				<0.10		
M2	7.85	400-480	>10		>27	<0.22	<0.005	<0.015	<1.5	<2.0	<1	<0.6		<0.5					<0.005	
M3	7.85	477-534	>9		>16	<0.30	<0.002	<0.10	<1	<1.8	<1.6	<0.6		<0.4						
M40	7.85	578-655	>6		>8	>.45	<0.002	<0.01	<0.7	<1.4	<0.4	<0.5		<1.0						
U6	8.2	220-260		100 (-320F)					3	22	24	6			0.4	1.5	2			
L201	7.857	255	56		60	0.03	0.015	0.045	>6.40	>4.0	>16			0.75	>0.1	1				
TW	7.85	216	67			0.6	1.5		18	0.3			0.1							1.5
G350	7.85	172	20		>30	0.14	0.01	0.02	1.7					0.2						
HI	7.85	350	16		>10	0.32		0.025	1.5	0.5	1.2	0.3		0.6					0.002	
CL	7.95	200	45	120		0.02				10.5	17	2			0.04					

The TW, C4, C8, and CD steel plates were blast loaded by a sheet charge (*Figure 2*) prior to the explosion bulge test. The thickness of the sheet charge was varied in 2 mm increments from 2 mm to 8 mm. However, only 2 mm and 4 mm charge thicknesses were used for explosive bulge tests. The materials applied with 6 mm and 8 mm were used as the microstructural image references.

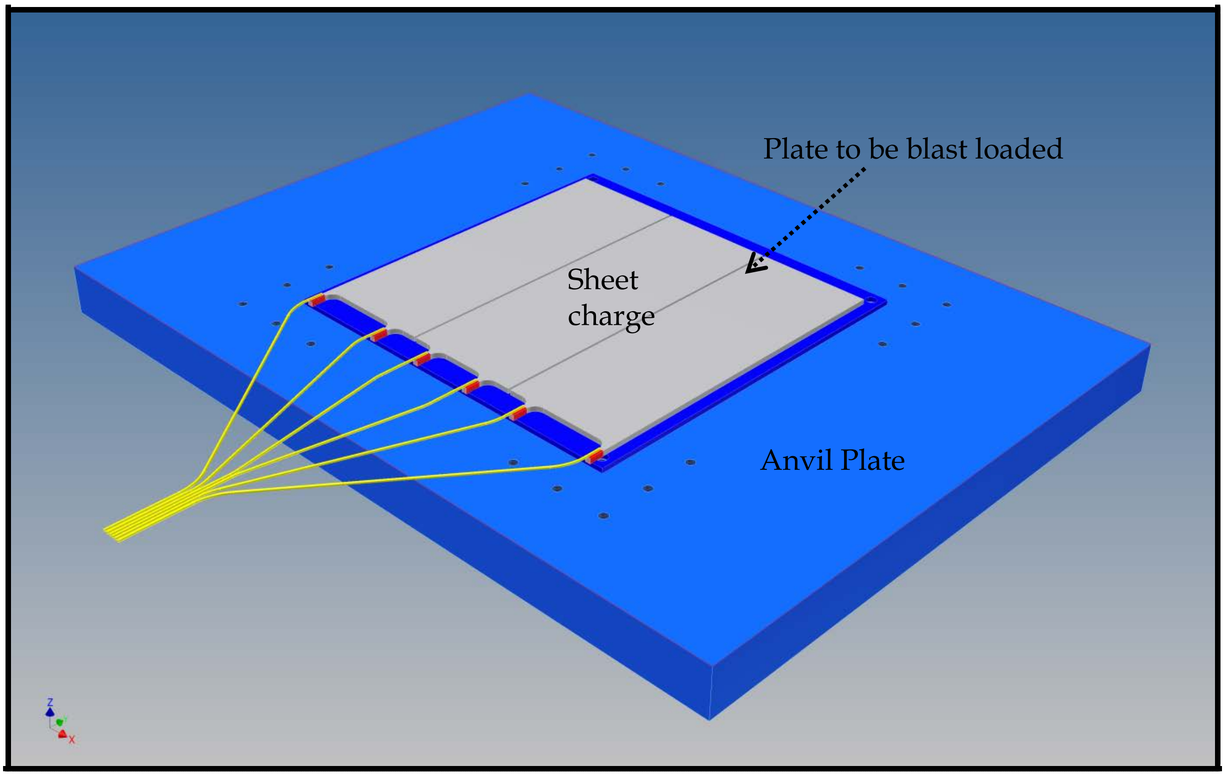


Figure 2: Design of plywood box for containing explosive during EXW trials with PE4 charge booster

3. Results and Discussion

3.1 Bulge Depth Comparison

Figure 3 shows a comparison of the bulge depths measured for each plate material, with respect to the number of blasts. After the 1st blast, steels M, A, and H had similar deformation. Steel B produced the largest bulge depth of the 4 plates tested. After repeated blasting, steel H failed after 5 blasts and steel B was seriously damaged after 6 blasts. However, both steels M and A were intact after 7 successive blasts.

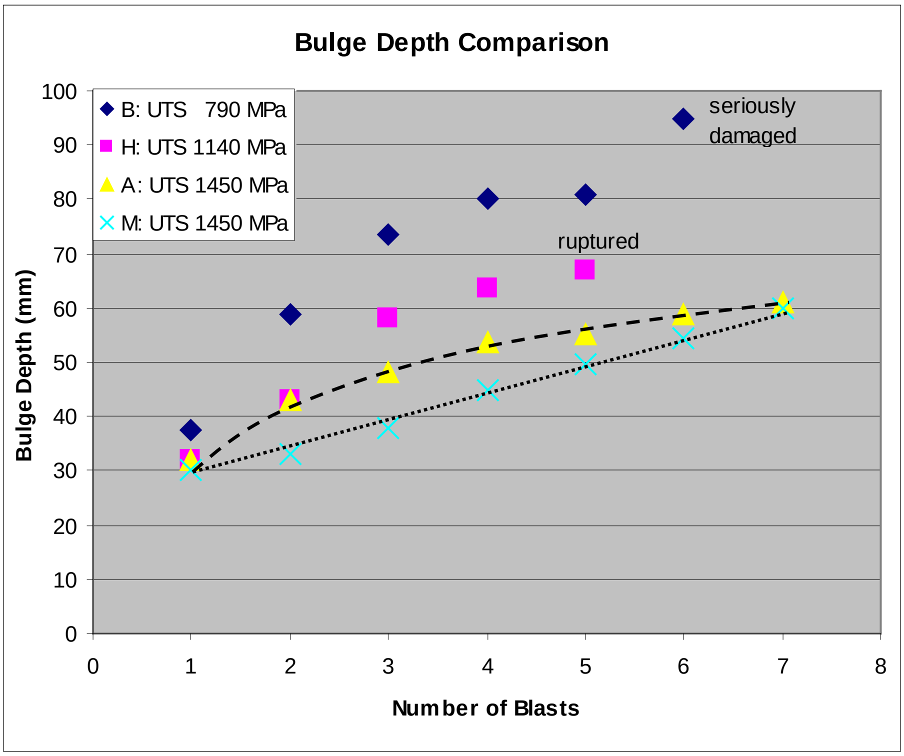


Figure 3: Bulge depth versus number of blasts for the four steel tested

It is notable that the trend of bulge depths vs. blast no. obtained from steel M shows a steady linear increase. This signifies good toughness, strength and deformation resistance under blast loading for this material. The trend of bulge depth vs. blast no. for steel A follows a curve from the second until the sixth blast, after which the bulge depth observed is almost identical to that of steel M. These materials have almost identical chemistry, microstructure and mechanical properties, although the Charpy impact toughness is approximately 30% greater for steel M (see 3.5).

In contrast, steels B and H show significantly larger bulge depth increases (especially steel B) from blasts 3 to 6, with severe cracking occurring in steel H after 5 blasts. As expected from yield stress data, steel B gave the greatest bulge depth, due most likely to lower carbon in solid-solution, as well as greater tempering. This results in reduced strength and hardness but increasing toughness and ductility in comparison with the other steels. Steel H showed a plateau trend with increasing blasts, until cracking occurred into the steel plate. This material possessed the lowest Charpy impact toughness of all four plate materials with 22 J at -40° C.

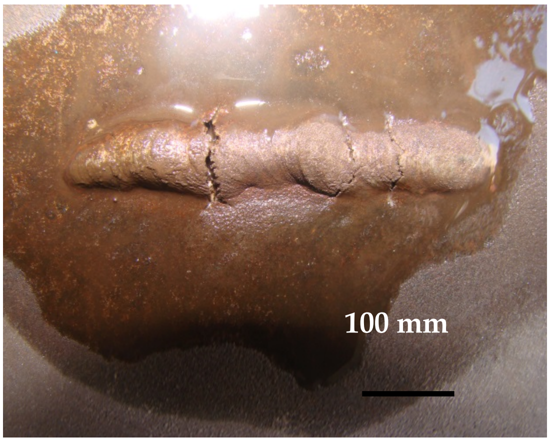
A summary of the bulge depths and associated behaviours observed at the site of the brittle hard-facing weld bead during EBT are described as follows.

3.2 First Blast

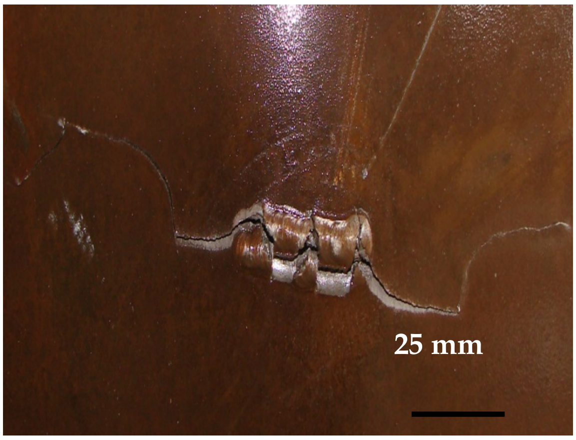
The first blast did not show any noticeable damage or difference in appearance between the four plate materials tested. Further, the bulge depths observed in all plates, with the exception of B plate (which was significantly deformed to 38 mm bulge depth), were similar (approximately 30 mm).

3.3 Subsequent blasts

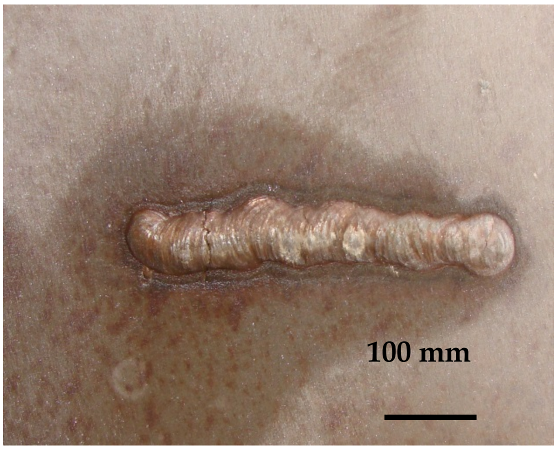
From *Figure 3* it is noteworthy that the extent of deformation is considerably less for the second and subsequent blasts than it is for the first blast. This is probably associated with work hardening of the plates. It is possible to exploit this phenomenon in future steels. For example, armour could be hardened by blasting prior to fabrication.



(a)



(b)



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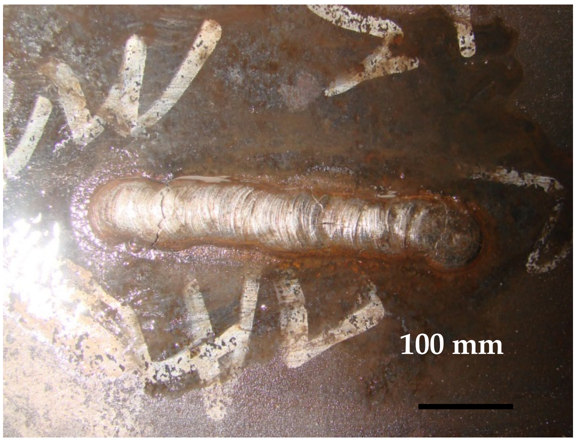


(d)

Figure 4: Surface appearance of the four plates (a) steel B, (b) steel H, (c) steel A and(d) steel M, after the 6th blast, clearly showing the brittle 'crack starter' weld bead and any cracking that had occurred. Only Steel H showed crack growth and this cracking was fully ductile.

In line with the requirements of the EBT, blasting was repeated for each of the plates to rank the materials in order of deformation resistance and to observe any crack growth. After the 4th blast, B steel showed some minor cracking across the hard-facing weld bead and into the plate. The other plates had no cracks outside the weld bead.

After the 7th blast, it was found that neither A steel or M steel showed cracking damage into the plates. It is thus concluded that these two materials have excellent properties in view of ductility, toughness and deformation resistance with respect to the EBT performed.

The appearance of crack starter weld beads after 6 blasts is shown for the four steels in *Figure 4*. It was observed that steel A (*Figure 4*c) and steel M (*Figure 4*d) did not show any crack initiation into the plates. Furthermore, these two plates showed very similar bulge depth after 6 blasts. However, it can be seen that steels B (*Figure 4*a) and H (*Figure 4*b) developed cracking into the plate material, with steel H showing extensive cracking to have occurred from the weld bead and into the plate. Therefore, steel H was shown to produce the most brittle behaviour under blast loading. Due to the extent of cracking, bulge depth was not recorded for steel H after the 6th blast.

3.4 'Pre-Blast' hardness and Microstructure results

In general, all these materials showed the increase of work hardening with repeated blasts. This implies that the blast concept can be used as a 'pre-blast concept' to maximize deformation resistance with minimum loss of toughness. *Figure 5* shows the hardness trends with the charge thickness.

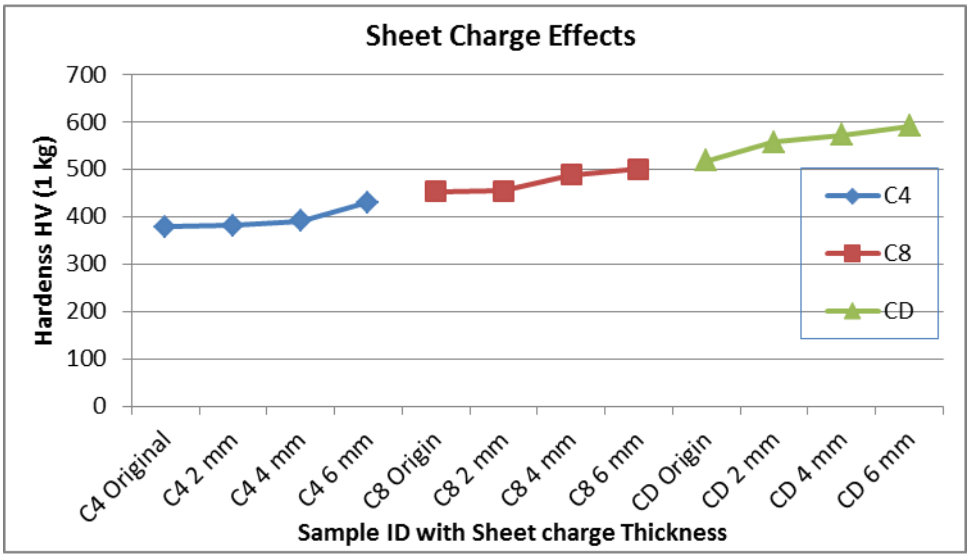
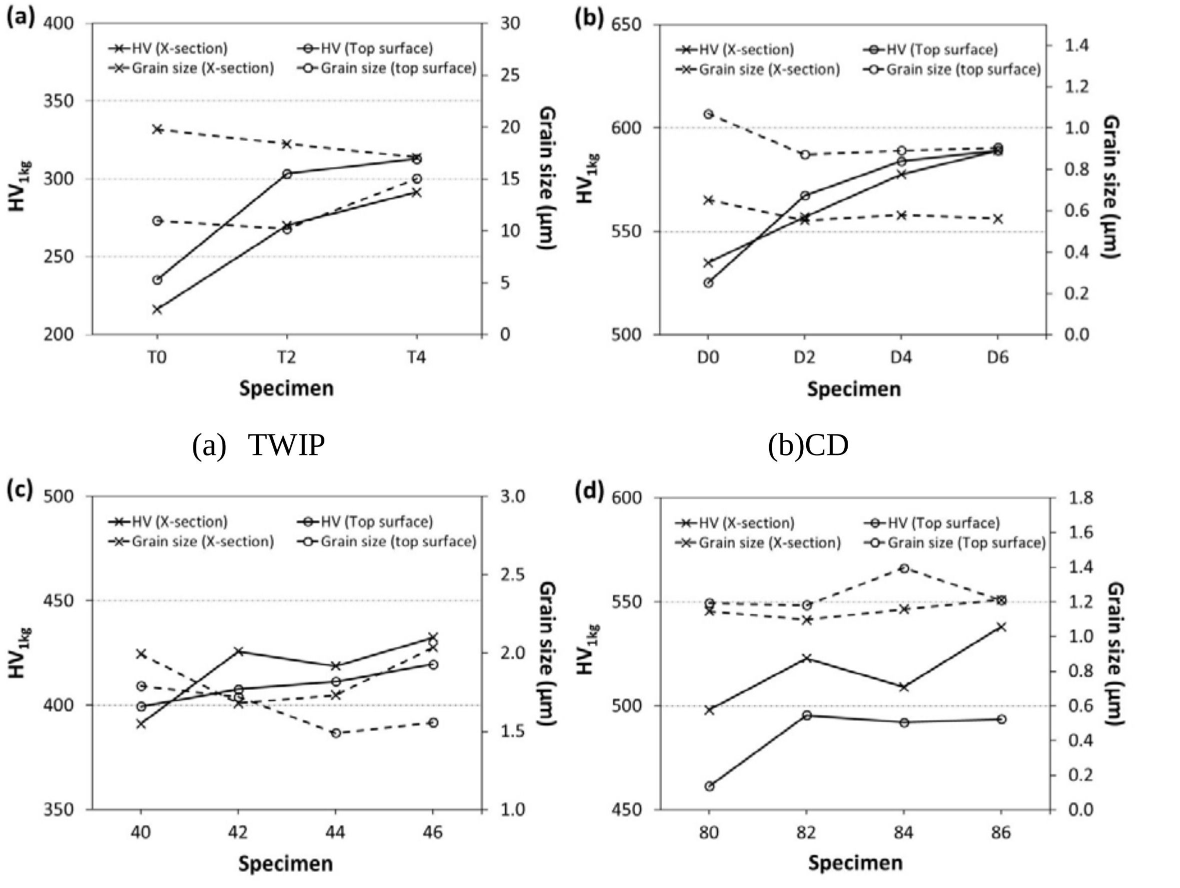


Figure 5: hardness development with blast loading of PE4 sheet explosive

The EBSD maps, misorientation plot, and the pole figure of each sample are listed in Appendix C, D, E and F for TWIP, dual phase, C4, and C8 steels. The correlated,

misorientation data between neighbouring points in a map, misorientation angle distribution is displayed. The (1 1 1) pole figure for TWIP steel (FCC crystal structure) is shown representatively, while (1 0 0) is chosen for Dual phase (DP), CR4, and C8 which are BCC.

The values of hardness/grain size versus different sample obtained by EBSD are plotted in *Figure 6* with both centre and top surface readings,



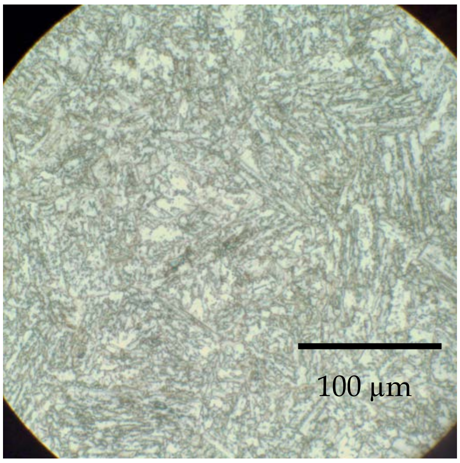
(a) TWIP (b)CD

(c) C4 (d) C8

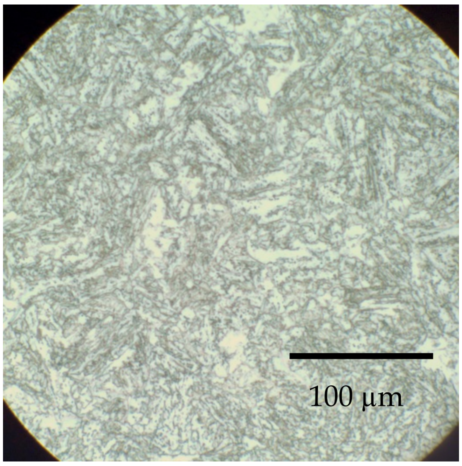
Figure 6. Hardness/grain size for four different samples: (a) TWIP steel, (b) CD Phase Steel, (c) C4 steel and d) C8 steel

Microstructures

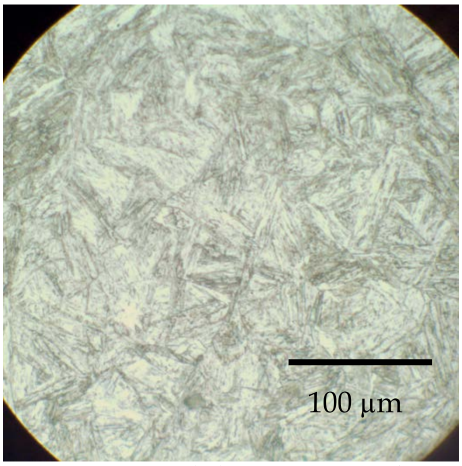
Most importantly, it also seems that blast loading of a plate in this way appears to have no detrimental effect on the subsequent blast performance of the plate. The plates showed no evidence of embrittlement as a consequence of the loading treatment and there were no other unexpected outcomes.



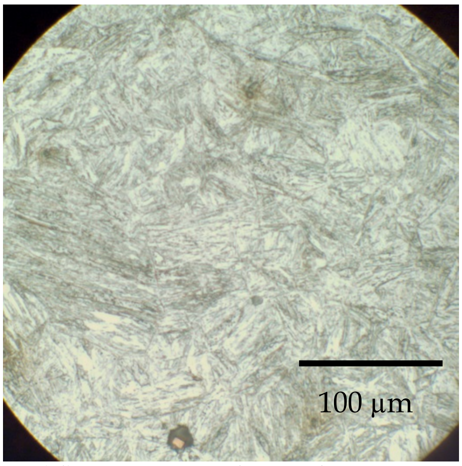
(a) C4 Original



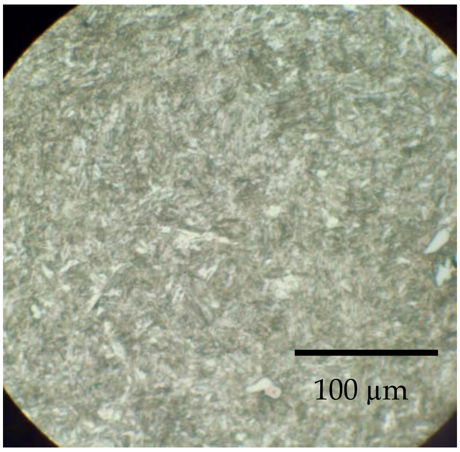
(b) 6 mm sheet charge



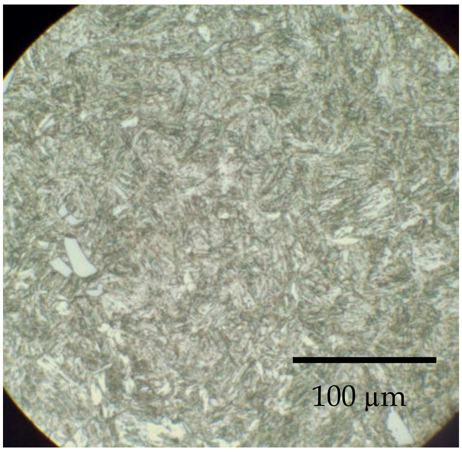
(c) C8 Original



(d) C8 6 mm sheet charge



(e) CD Original



(f) CD 6 mm sheet charge

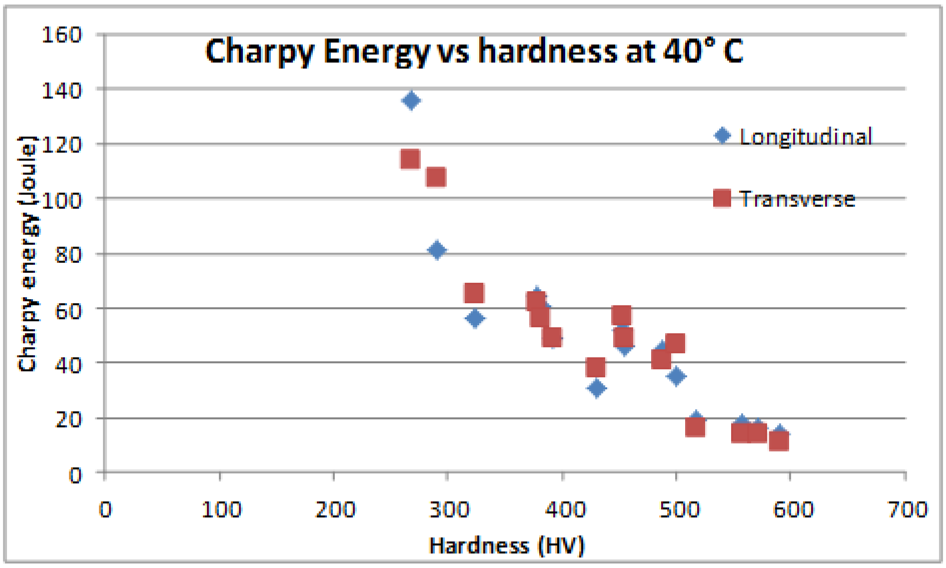
Figure 7: Microstructures of steels for impacted surfaces before and after blast loading with 6 mm sheet charge (1000x)

The plates were subjected to metallographic inspection and to sub-size Charpy testing to further ensure that they have not been adversely affected by the blasting. *Figure 7* shows the microstructures of all the samples in use with 1000x magnification for the as-received samples and the samples under 6 mm sheet charge blast.

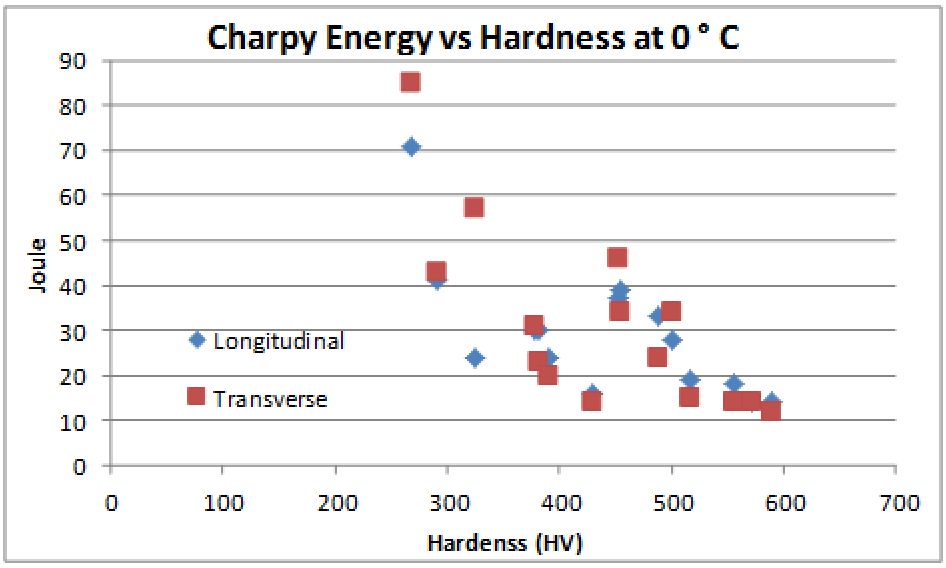
Appendix B shows the more detailed microstructures. As can be seen in Figure B1 and B2, there were no signs of micro-cracks for C4 and C8 series of steels but showed cracked particles in all 3 pre-blast CD steel specimens (CD2, CD4 and CD6) in Figure B3 and Figure B4. The CD cracks, however, did not appear to propagate into the matrix. There was also some evidence of dis-bonding of particles coupled with and isolated from cracking as can be seen in Figure A8. The CD steels have the highest hardness (650 HV) of the samples under the test. It seems that the as-received material has already achieved its maximum work hardening; the material undertakes no additional work hardening by the pre-blast loading technique.

3.5 Charpy Energy –Hardness relationship

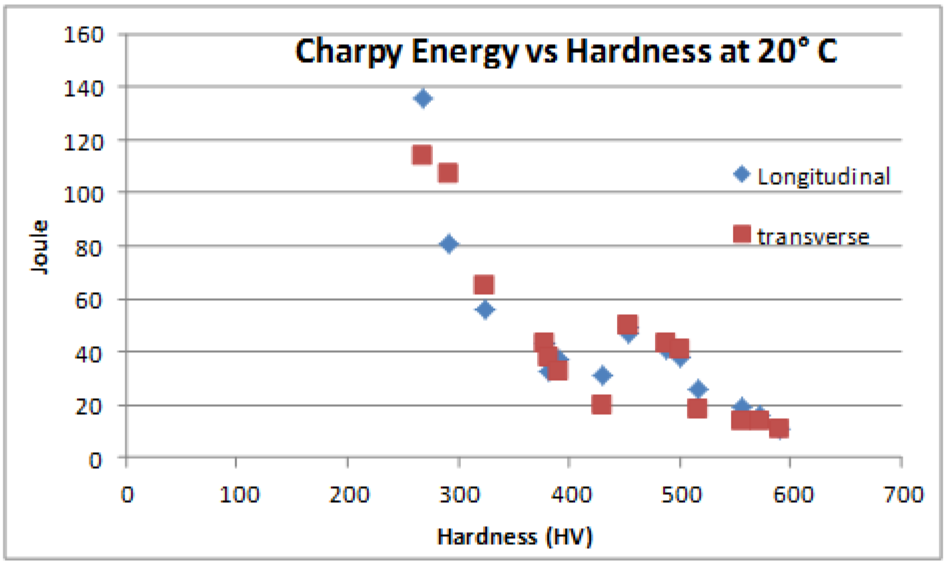
Figure 8 shows the relationships between the Charpy impact energy and hardness. Regardless of the rolling direction, the Charpy energy dropped to a level less than 20 Joule when the hardness exceeded 500 HV. These energy results would normally be classified as 'brittle'.



(a)



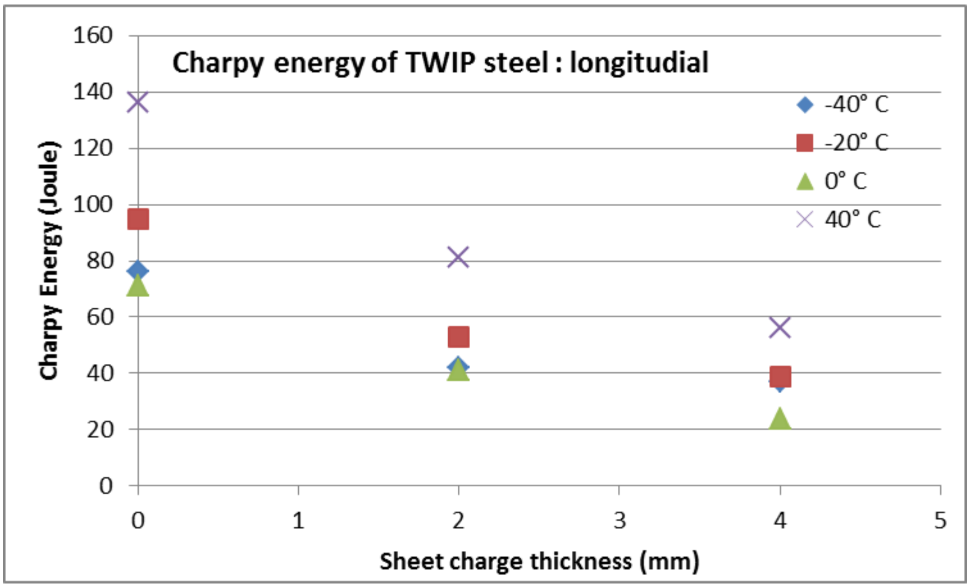
(b)



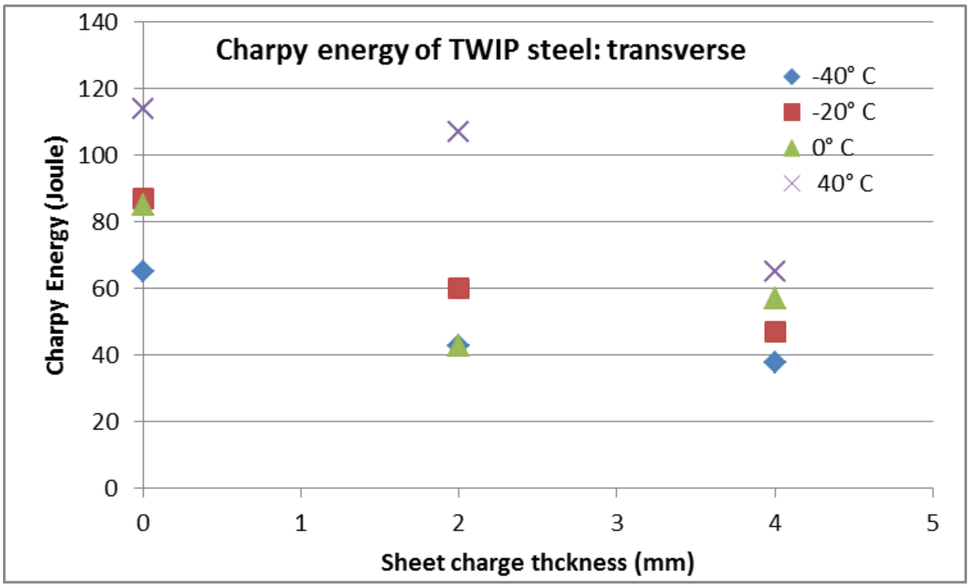
(c)

Figure 8: The Charpy energy vs hardness at various temperatures

Figure 9 shows the Charpy energy relationship against sheet charge thickness of TWIP steels. With 2 mm sheet charge blast, Charpy energy maintains more than 40 Joules which is generally accepted as 'tough' but with 4 mm sheet charge, the energy dropped near to 20 Joule which is 'brittle'. It is clear in this Figure that the TWIP steel has a reasonably acceptable toughness level, regardless of the rolling direction, up to 2 mm of sheet charge.



(a)



(b)

Figure 9: Charpy energy of TWIP steel against sheet charge thickness along the rolling direction

3.6 EBSD

For all specimens, there is a trend of increase in through-thickness hardness as the sheet charge is increased and, for most cases, the thicker the sheet charge, the harder the material. The effect on grain size isn't consistent and requires further investigation. The grain size of TWIP centre decreases as the sheet charge becomes thicker while the opposite is found on the top surface. The 6 mm sheet charge blast increases the top surface grain

size of TWIP steel by about 40%. The grain size of dual phase steel decreases to a stable value after a sheet charge blast regardless of the sheet thickness; the centre grain size drops nearly 20% while the top surface grain size decreases about 15%. It should be noted, however, that the grain sizes are all extremely small, about 0.1 µm.

The C4 cross-section grain size decreases about 15% (0.3 µm) after both the 2 mm and 4 mm sheet charge blast and it remains at the same level after the 6 mm sheet charge blast. While in the case of C4 top surface, the grain size slightly goes down, 0.1, 0.3, and 0.2 µm, after the 2 mm, 4 mm and 6 mm sheet charge blasts respectively. For C8 cross-section, the value rises (about 0.1 µm) after 4 mm and 6 mm sheet charge blasts.

4. Conclusions

This work compared four commercial armour steels, possessing a range of steel chemistries and mechanical properties, with respect to their resistance to multiple blast loadings. Both toughness and deformation resistance of the steels were assessed by bulge depth measurements and cracking assessments using the EBT. A number of conclusions that may be drawn from these investigations are:

1. Results of multiple-shot crack starter Explosion Bulge testing show that Steels A and M perform well with moderate bulge development and minimal evidence of crack growth.
2. Under identical test conditions, Steel H showed increased deformation and the steel ruptured after the fifth blast.
3. Steel B, which is not strictly an armour steel, showed greatest deformation after multiple loadings
4. Pre-blasting of armour materials gave a measureable increase in hardness but with compensation of toughness.
5. The grain size variation by rapid blast is strongly directional.
6. As- received materials with relatively low hardness and high toughness such as TWIP steel have a good potential to be hardened with this pre-blast technique with some loss of toughness.

5. Acknowledgements

We gratefully acknowledge the assistance of John Williams and Frank Marian as firing officers and Trevor Delaney as a safety officer and Dr Chris Anderson as a technical advisor.

Appendix A: Test Plate Design

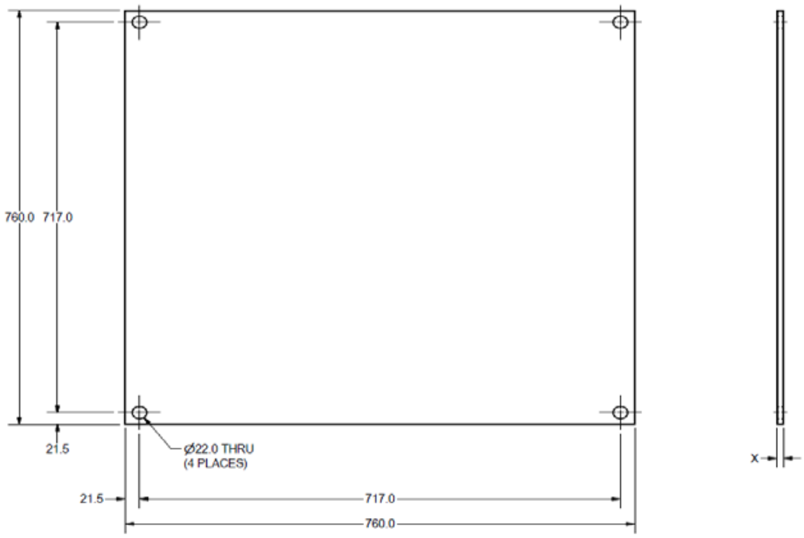


Figure A1: Plate design for dual plates. The bolts and nuts are applied to the dual plates to hold them tightly together.

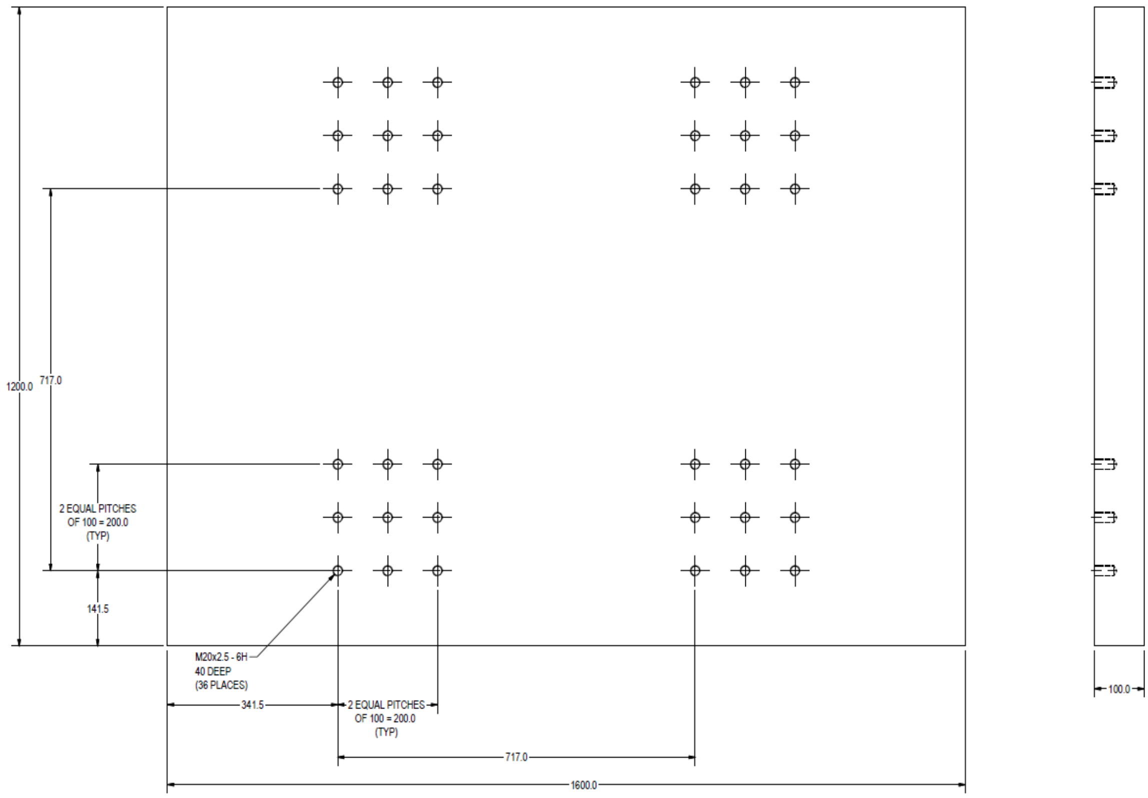


Figure A2: Design of base plate for EXW and blast hardening trials. The material of this plate is Grade 250 mild steel.

Appendix B: Microstructures before and after Blasing with Sheet Charge

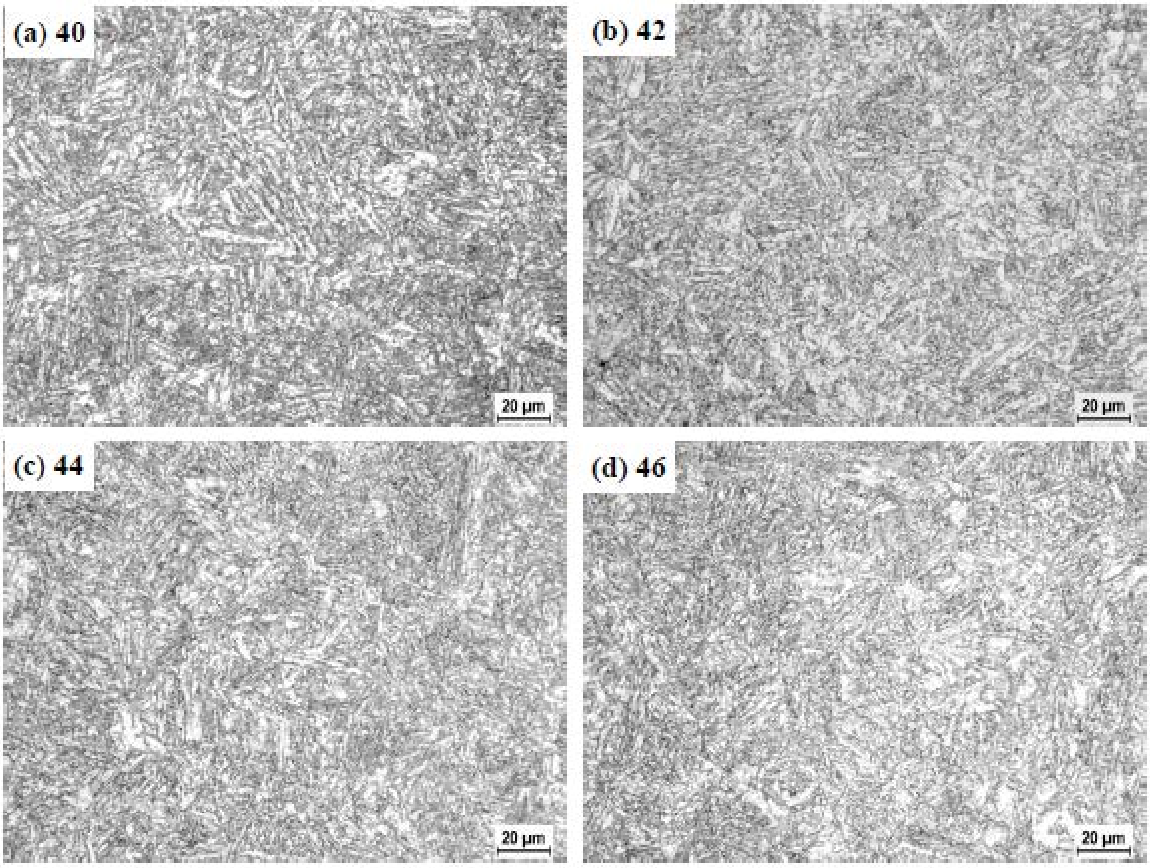


Figure B1: Optical microstructure of C4 a) As-received, and with pre-blast using a sheet charge of thickness: (b) 2mm, (c) 4 mm, and (d) 6 mm. 500x magnification, 2% Nital etch.

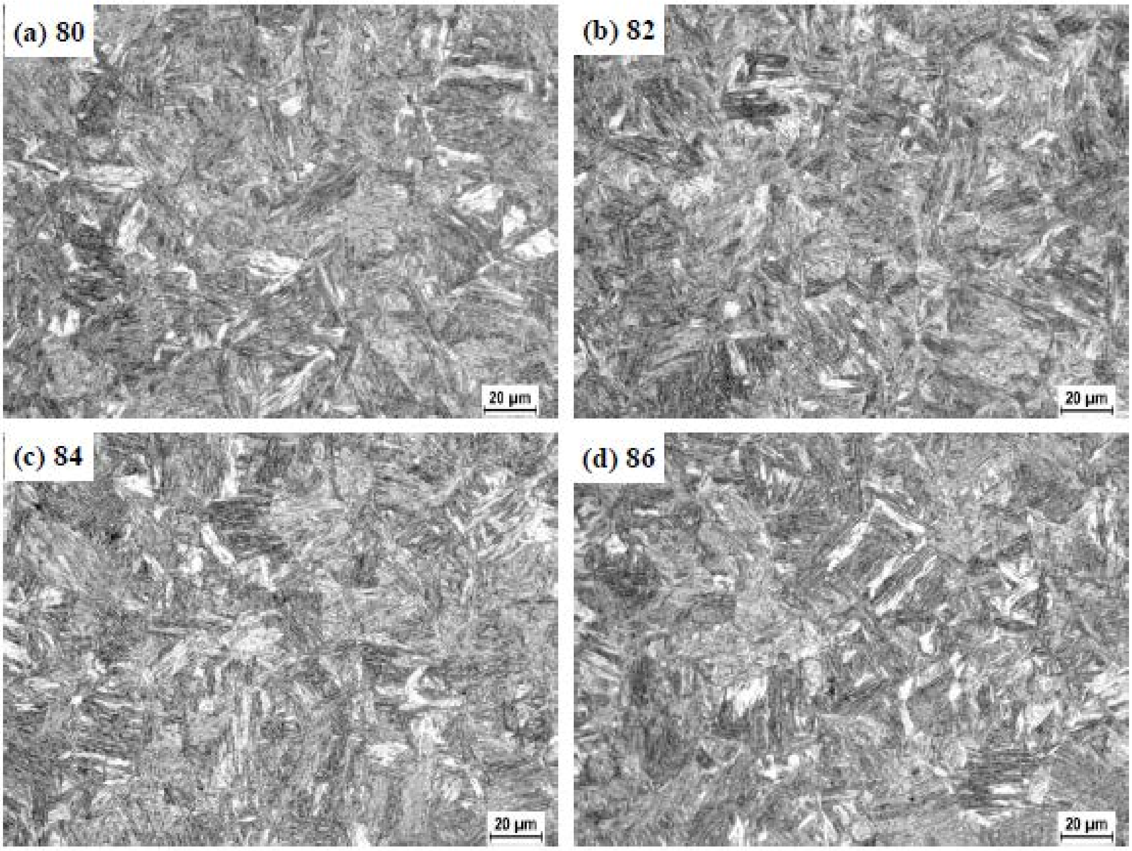


Figure B2: Optical microstructures of C8: (a) As-received, and with pre-blast using a sheet charge of thickness: (b) 2 mm, (c) 4 mm and (d) 6 mm. Optical 500x magnification. SEM 5000x magnification, 2% Nital etch.

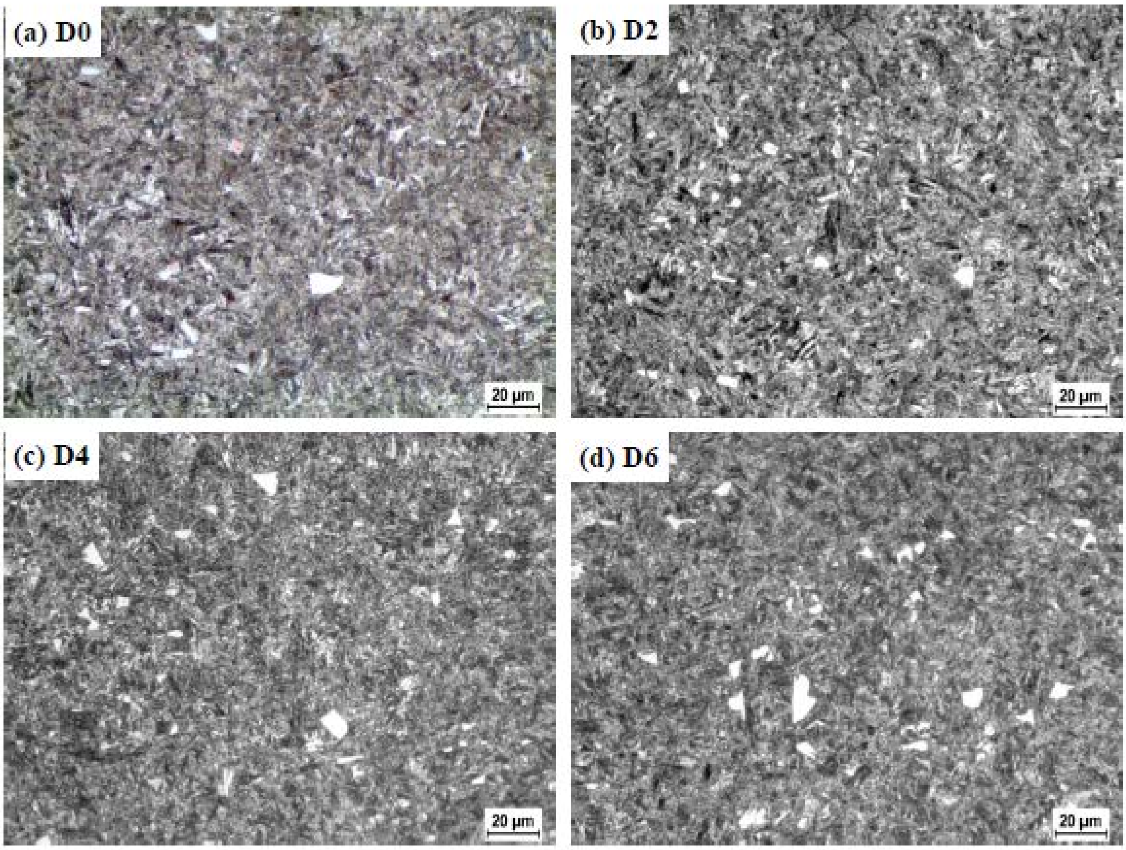


Figure B3: Optical microstructures of CD (a) As-received, and with pre-blast using a sheet charge of thickness: (b) 2 mm, (c) 4 mm and (d) 6 mm. Optical 500x magnification, 2% Nital etch.

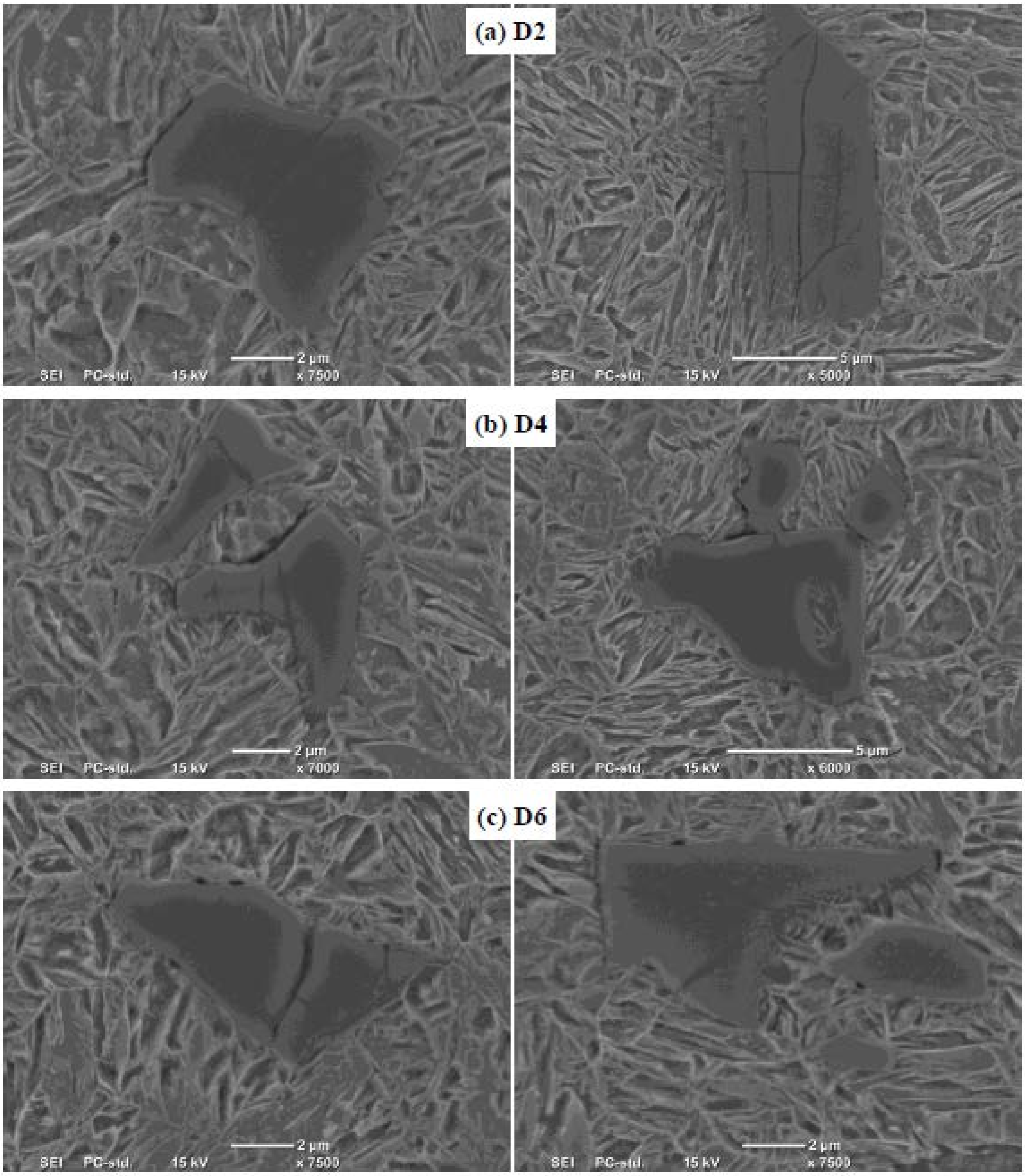


Figure B4: SEM micrograph of cracked particles in the CD steel with pre-blast using a sheet of charge of thickness: (a), 2 mm, (b) 4 mm and (c) 6 mm. Various magnifications as indicated on micrograph, 2% Nital etch. It is ware that the titanium carbides (large islands) started crack from D2 sample and broken in pieces from D4 and D6 samples but clearly isolated from the matrix.

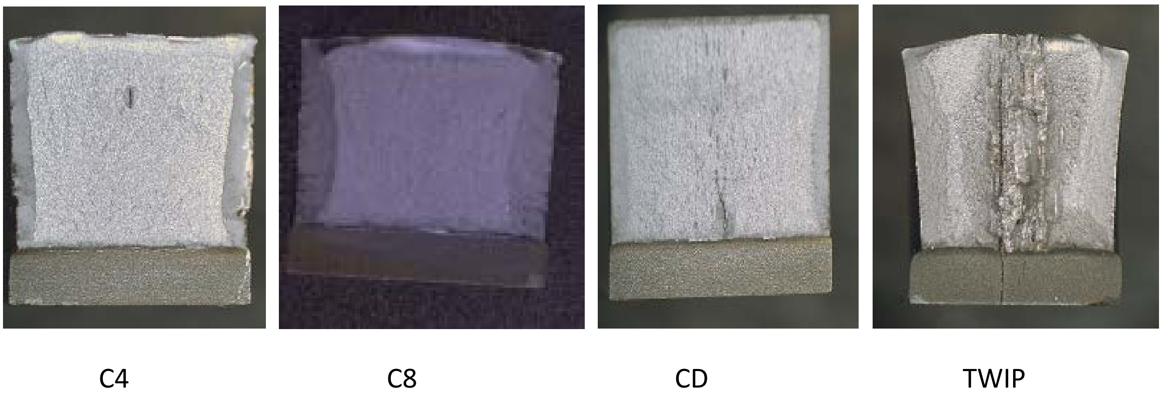


*Figure B5: Optical micrographs of fractured samples at -20° C. The % of fibrocity are 20% (C4), 30% *C8), 10% (CD), and 100 % (TWIP).*

Appendix C: Values of Hardness and Grain Size for Plates subjected to Blast

	Sample (Centre)				Sample (Top surface)			
	Hardness (HV_{1kg})		Grain size (µm)		Hardness (HV_{1kg})		Grain size (µm)	
	Mean	Stdev*	Mean	Stdev	Mean	Stdev	Mean	Stdev
T0	216.26	4.99	25.01	18.14	235.34	16.02	19.26	18.01
T2	270.24	3.89	24.60	20.46	303.28	5.17	17.68	16.33
T4	291.58	6.55	23.74	18.84	312.94	7.93	22.04	18.80

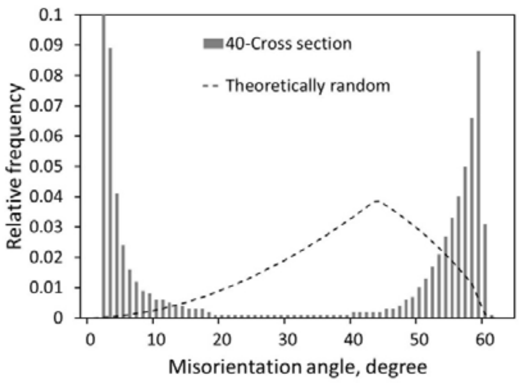
	Sample (Centre)				Sample (Top surface)			
	Hardness (HV_{1kg})		Grain size (µm)		Hardness (HV_{1kg})		Grain size (µm)	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
40	391.18	7.04	2.95	2.95	399.40	4.52	3.19	3.5
42	425.68	5.63	2.84	2.97	407.70	2.33	3.2	3.54
44	418.78	8.33	2.88	3.02	411.42	4.14	2.6	2.6
46	432.38	12.35	3.11	2.91	419.58	17.48	2.88	2.87

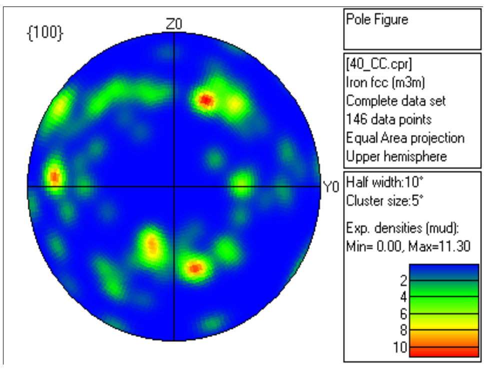
	Sample (Centre)				Sample (Top surface)			
	Hardness (HV_{1kg})		Grain size (µm)		Hardness (HV_{1kg})		Grain size (µm)	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
80	498.06	8.46	1.97	1.75	461.34	15.56	2.22	2.94
82	522.86	4.82	1.92	1.63	495.60	4.69	2.25	2.23
84	509.12	12.76	1.99	1.82	492.16	5.92	2.34	2.33
86	538.08	4.06	2.05	1.85	493.61	11.96	2.22	2.31

	Sample (Centre)				Sample (Top surface)			
	Hardness (HV_{1kg})		Grain size (µm)		Hardness (HV_{1kg})		Grain size (µm)	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
D0	534.96	13.12	1.04	0.88	525.24	3.64	1.77	1.13
D2	557.02	9.39	1.06	0.92	567.36	2.41	1.5	1.07
D4	577.62	8.66	1.07	0.92	583.98	3.68	1.44	0.99
D6	589.08	5.14	1.04	0.9	589.10	4.95	1.47	1.06

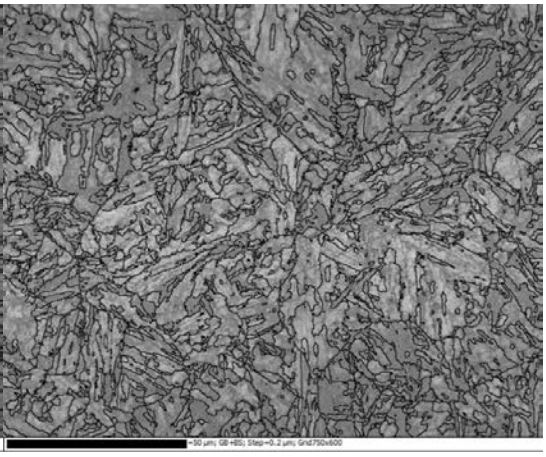
Appendix D: Microstructures and texturing effects

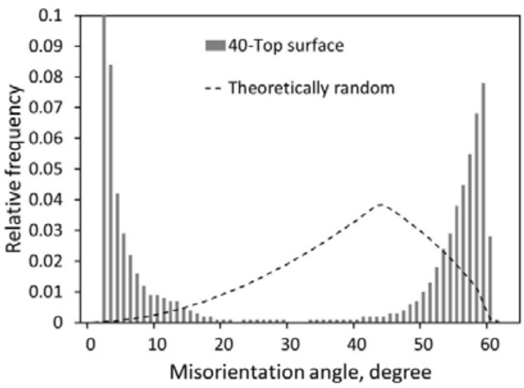
C40 Centre

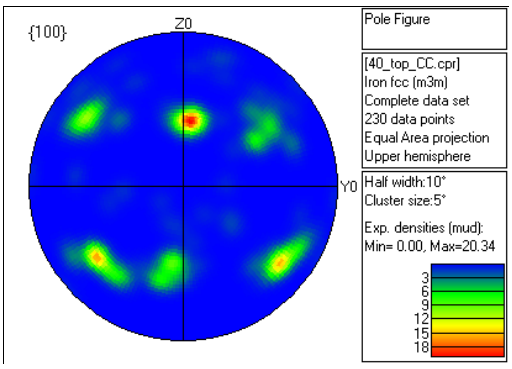




C40 Top surface

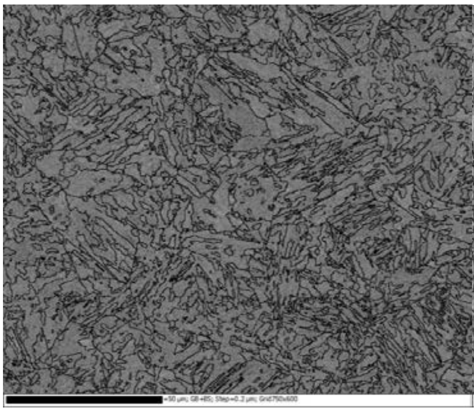


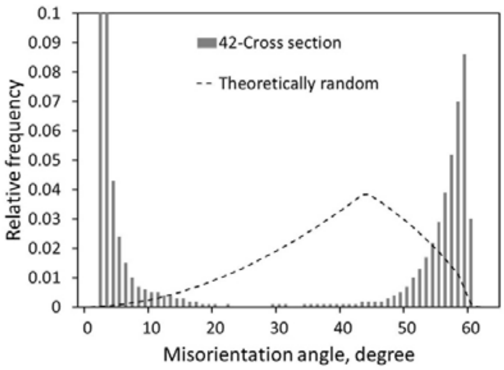


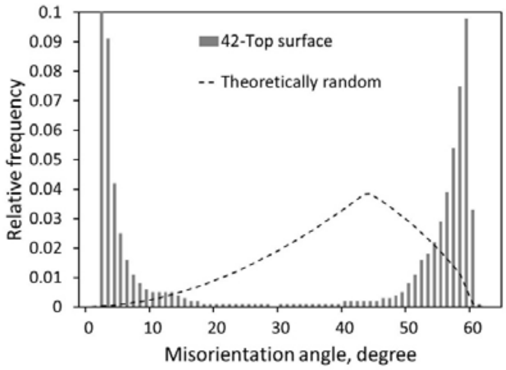


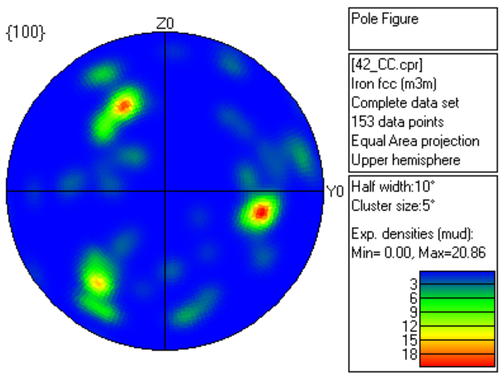
C42 Centre

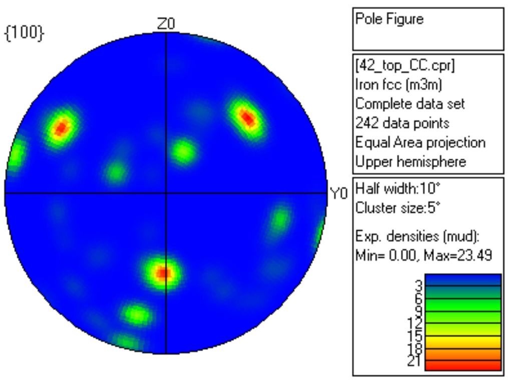
C42 Top surface



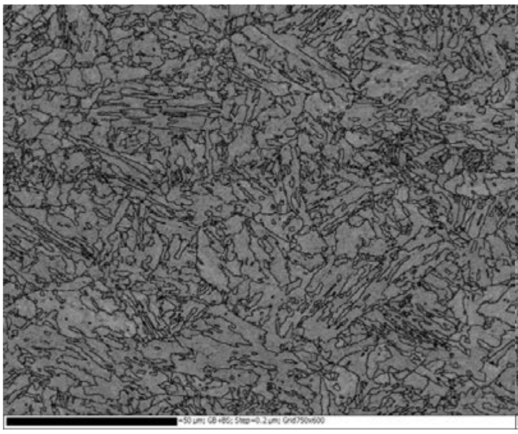


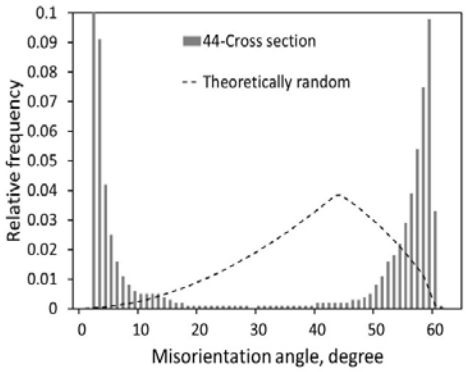


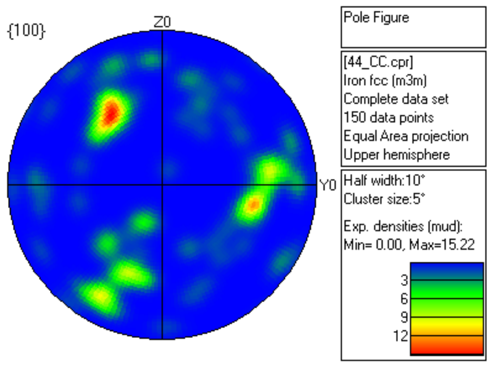




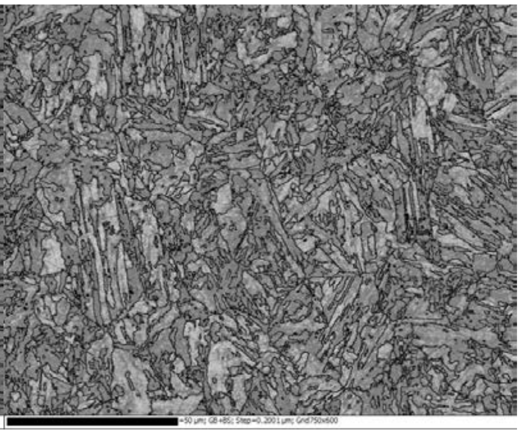
C44 Centre

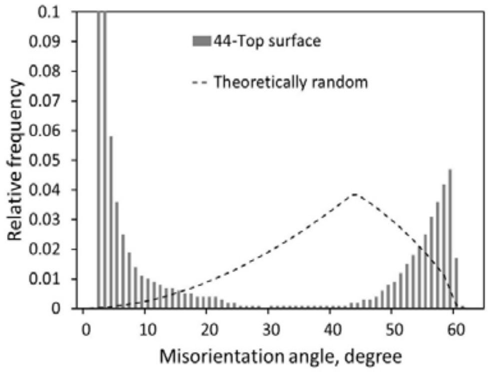


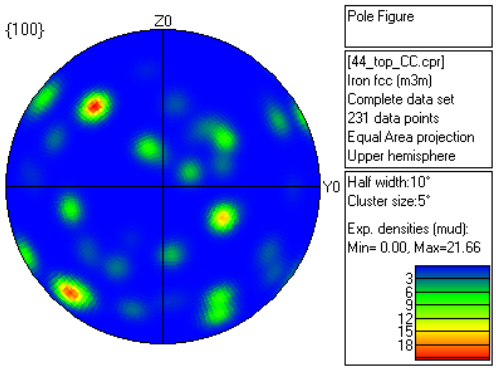




C44 Top surface

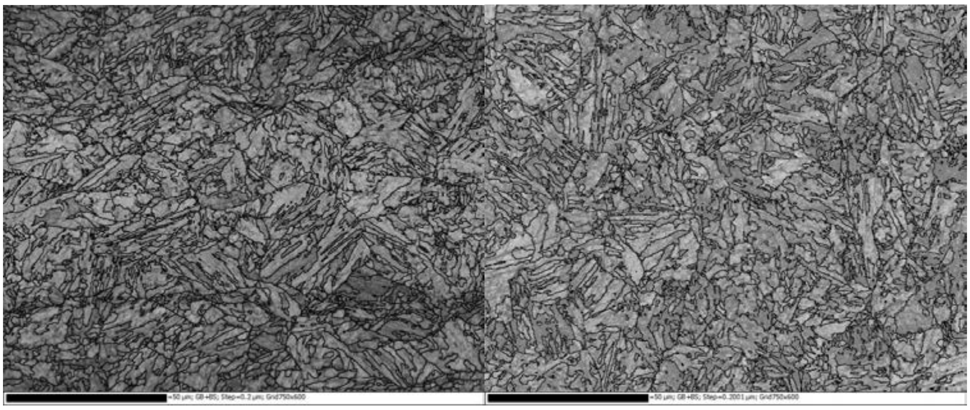


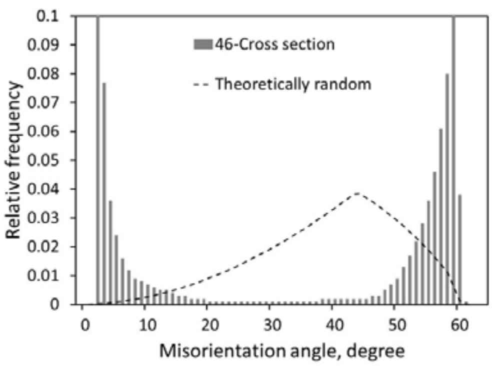


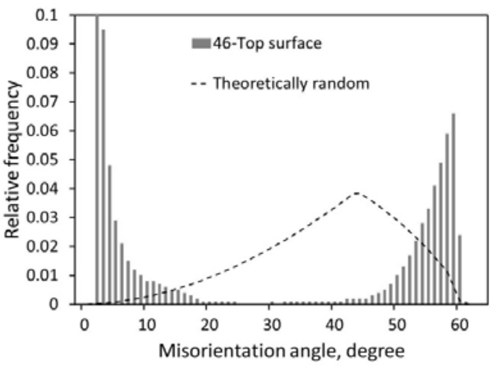


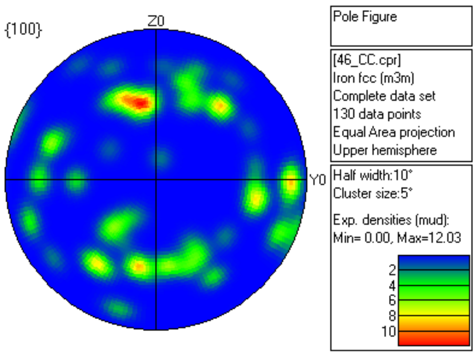
C46 Centre

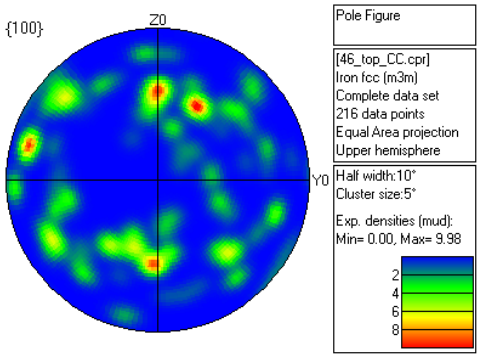
C46 Top surface





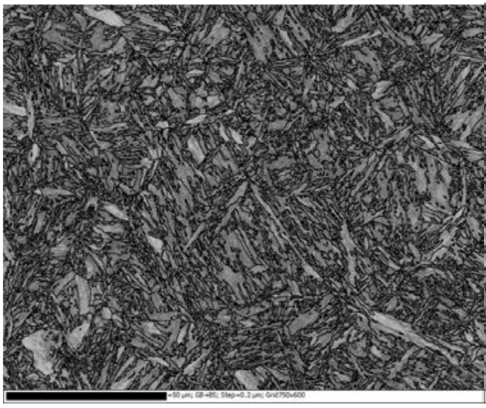


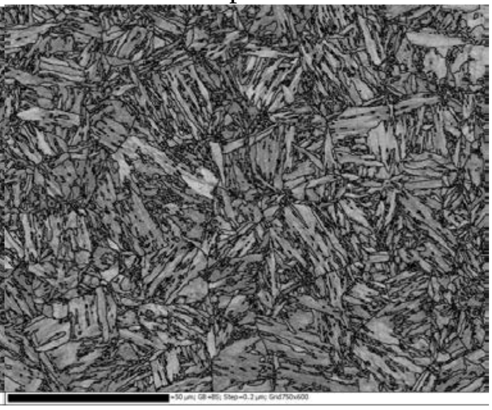


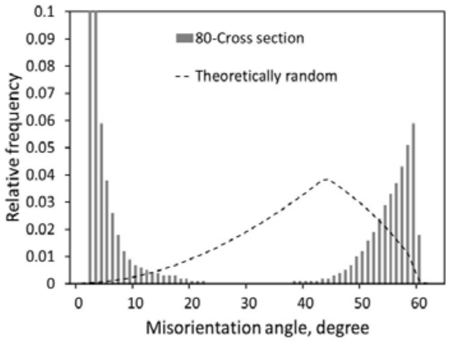


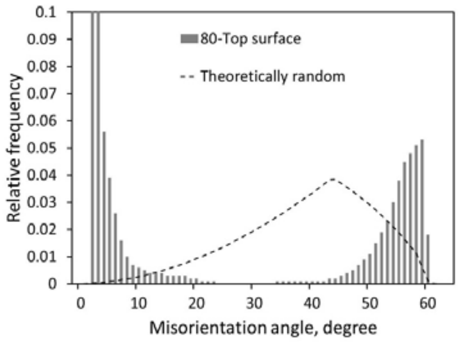
C80 Centre

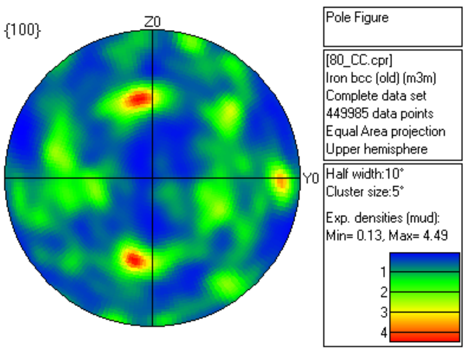
C80 Top surface

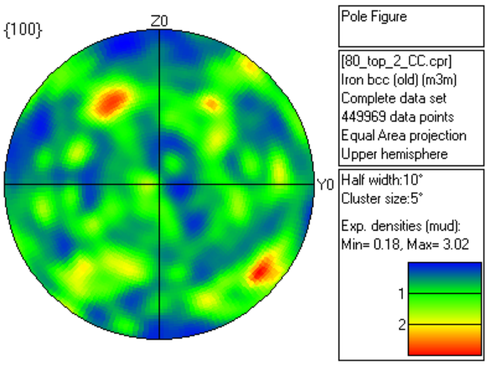




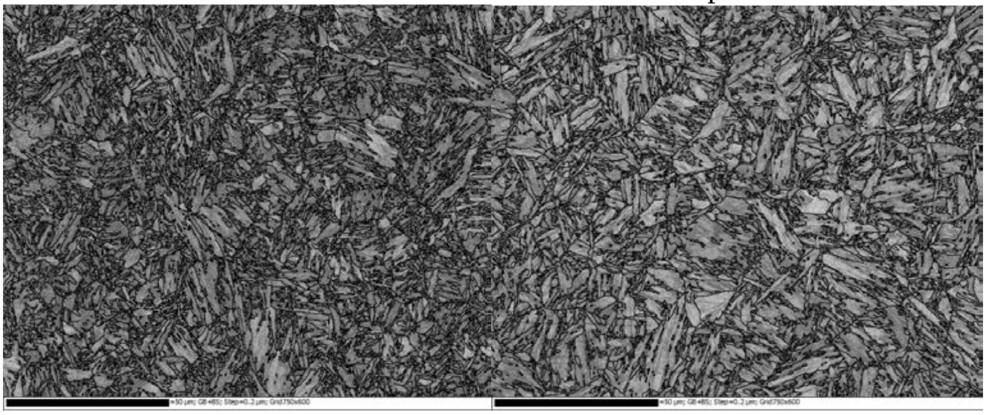


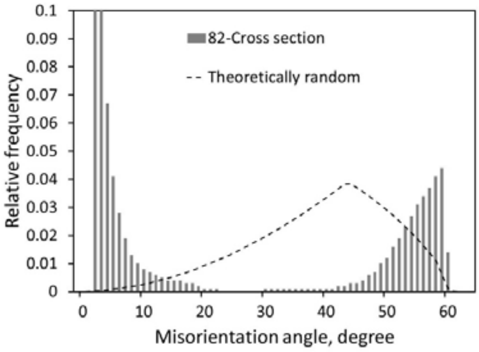


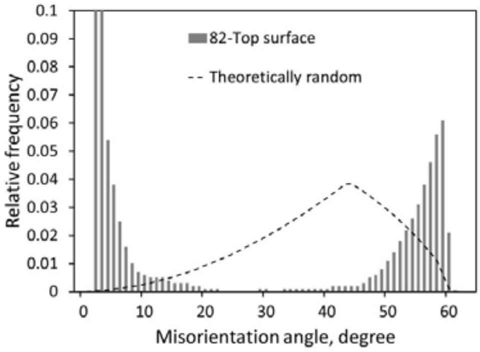


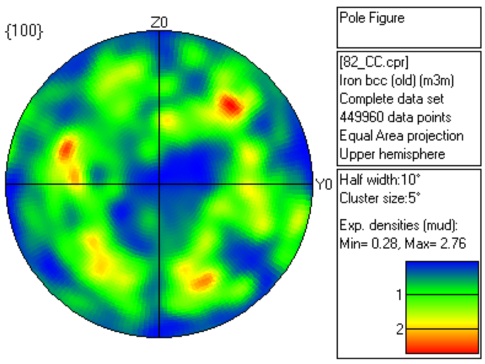


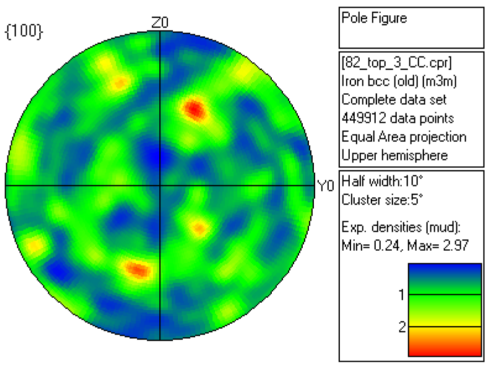
C82 Centre C82 Top surface





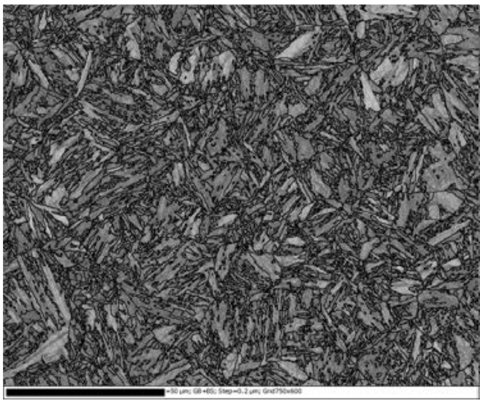


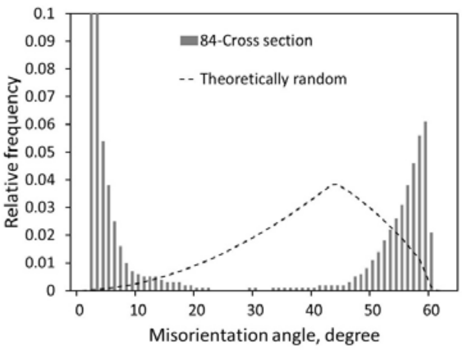


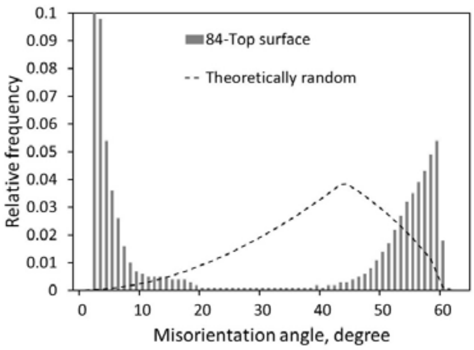


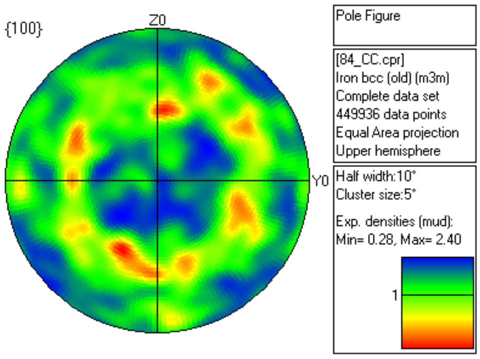
C84 Centre

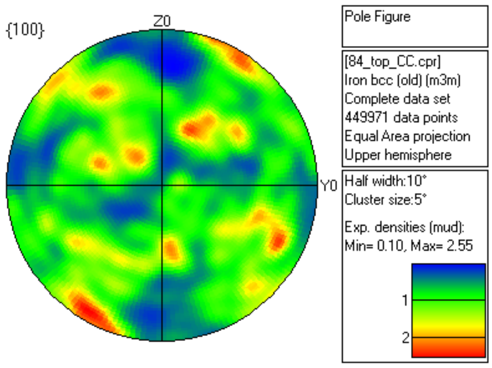
C84 Top surface



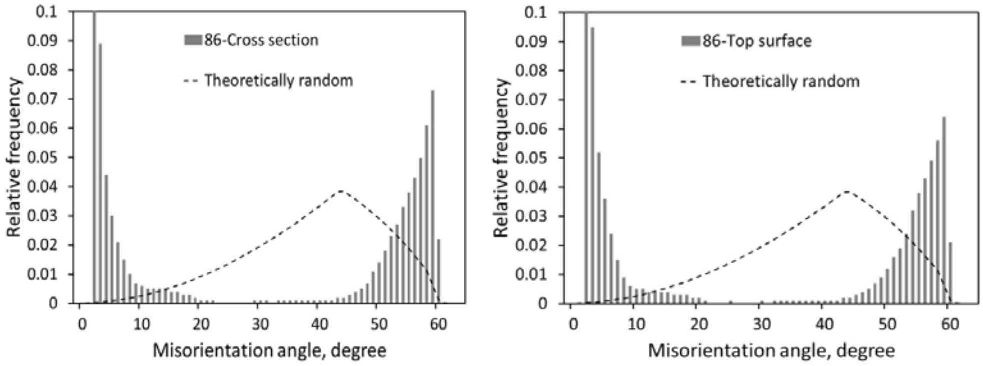


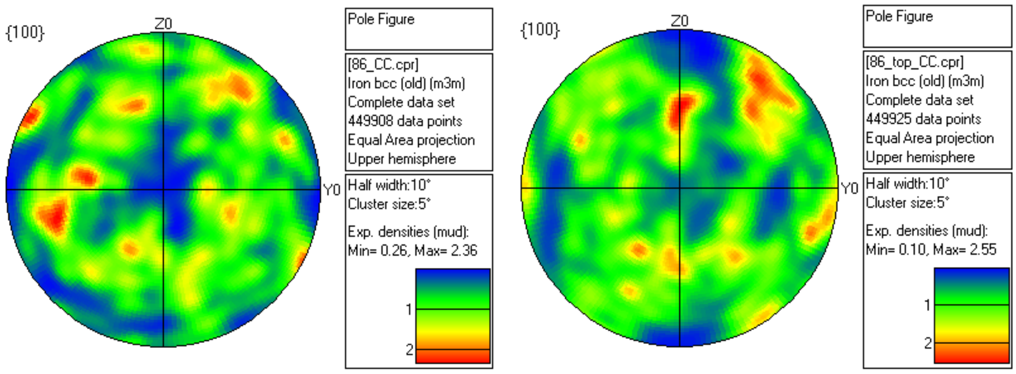






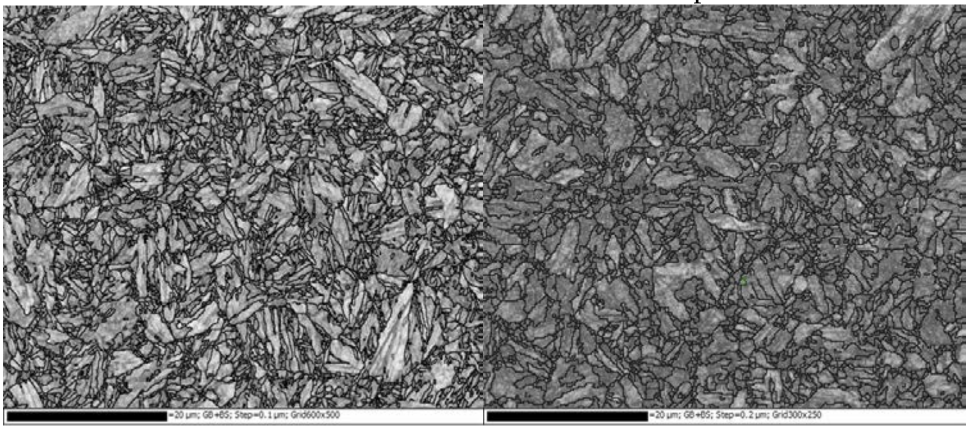
C86 Centre C86 Top surface

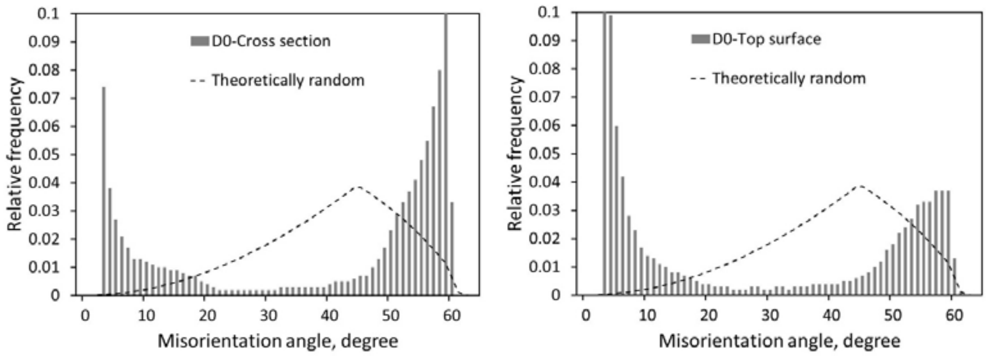


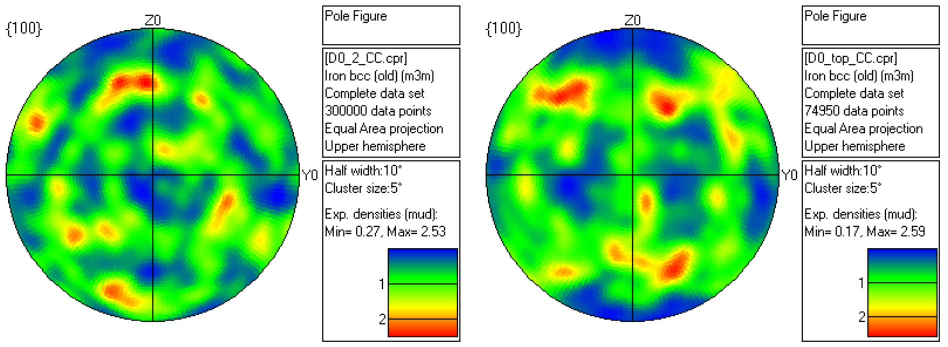


D0 Cross-section

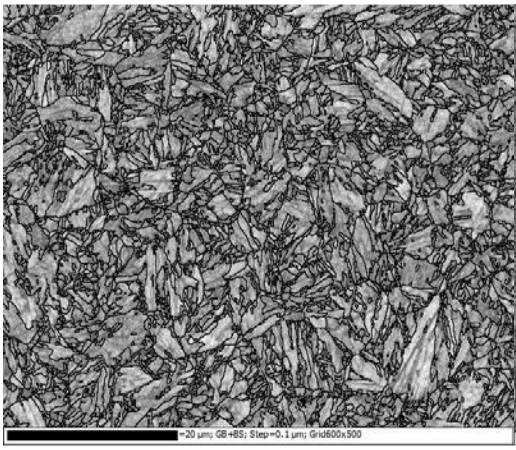
D0 Top surface



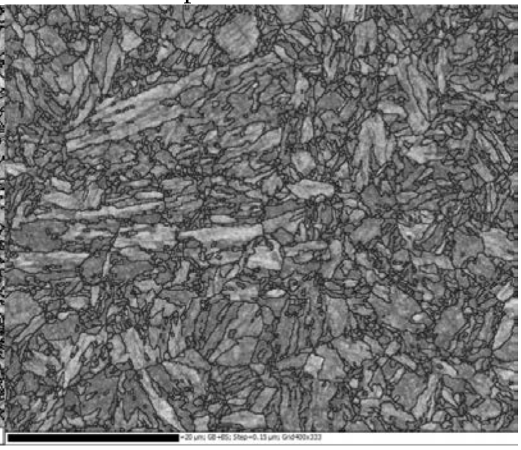


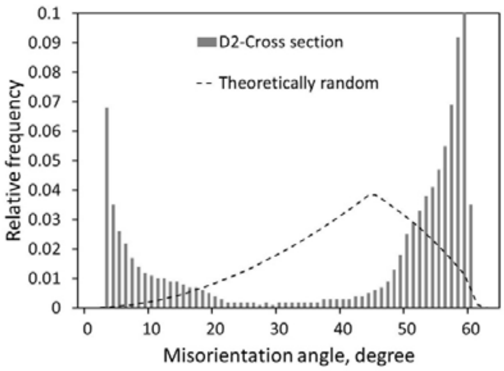


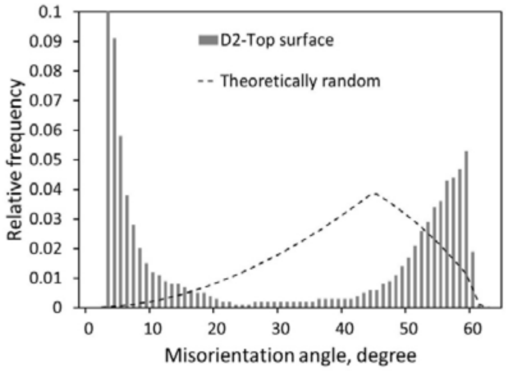
D2 Centre

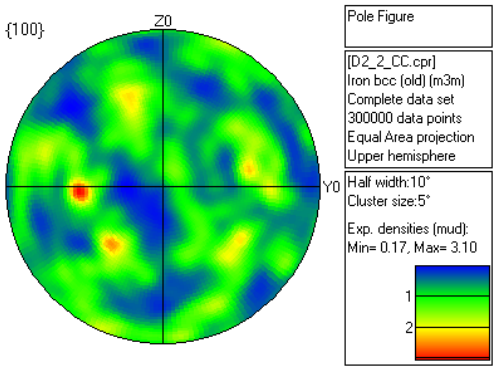


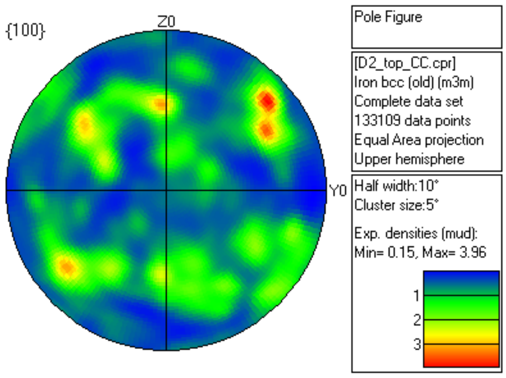
D2 Top surface











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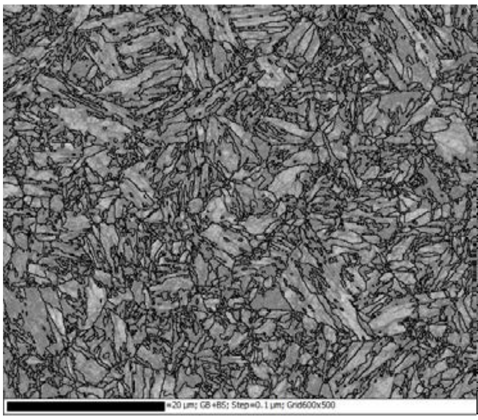

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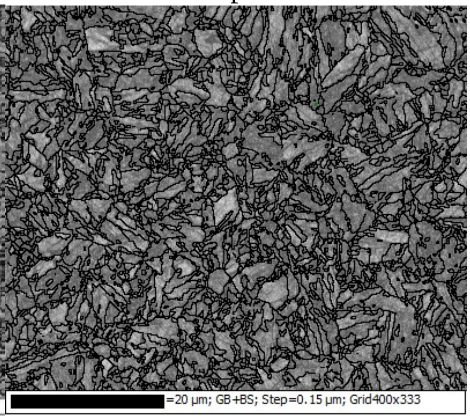
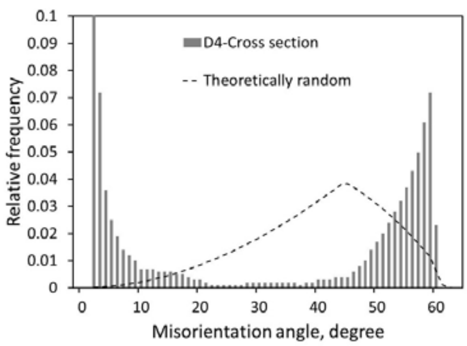
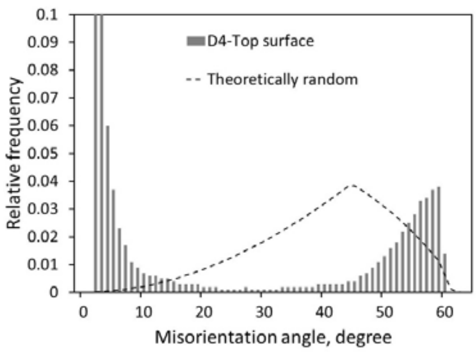
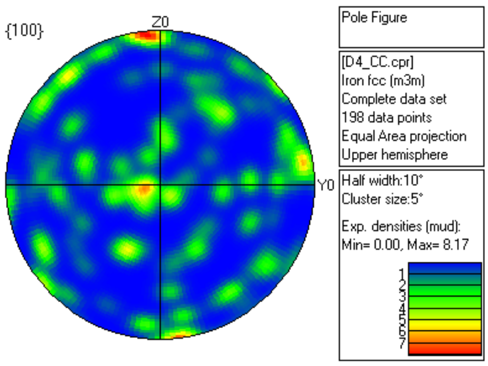
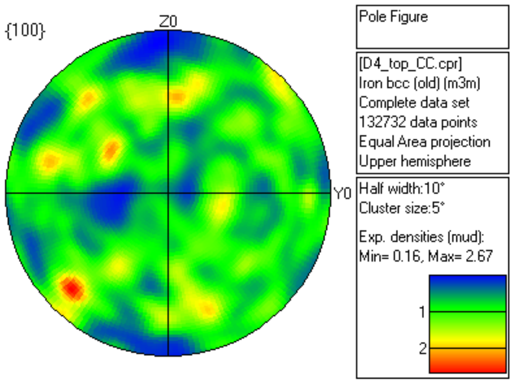




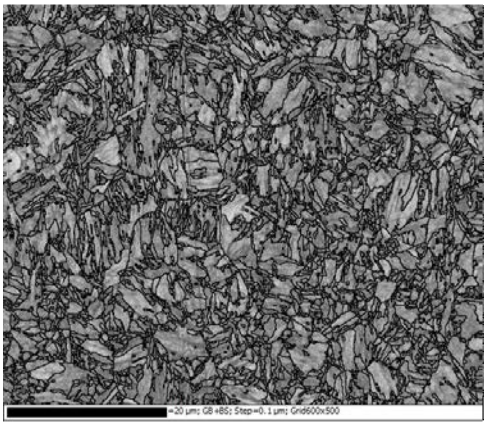


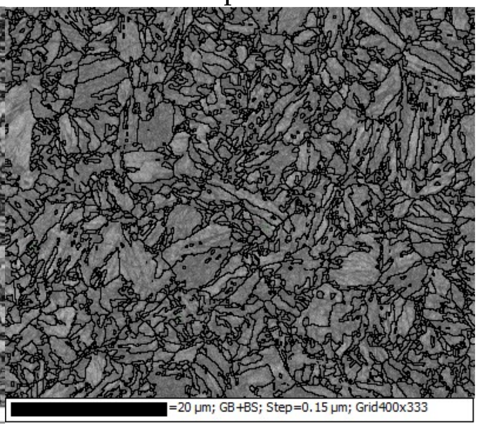


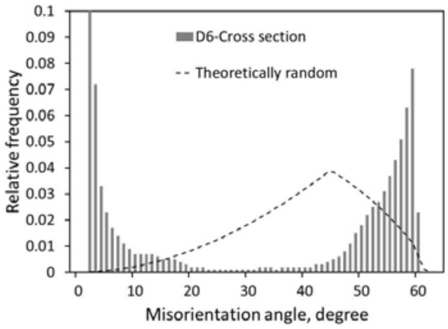


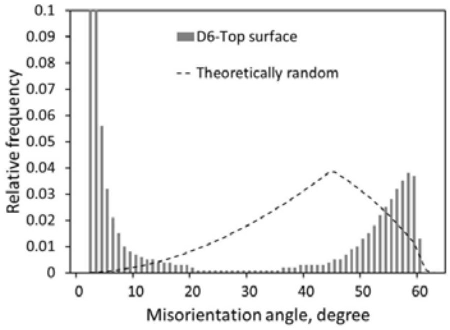
D6 Centre

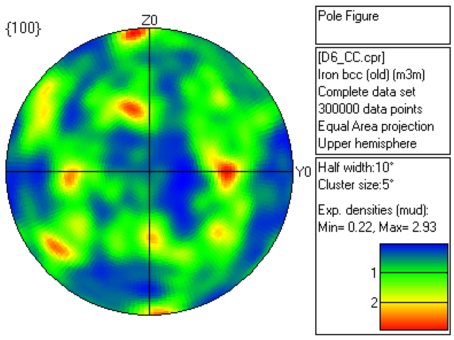
D6 Top surface

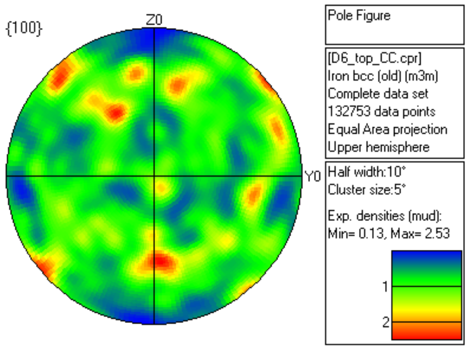






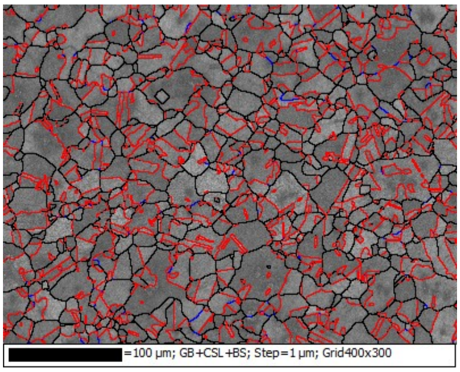




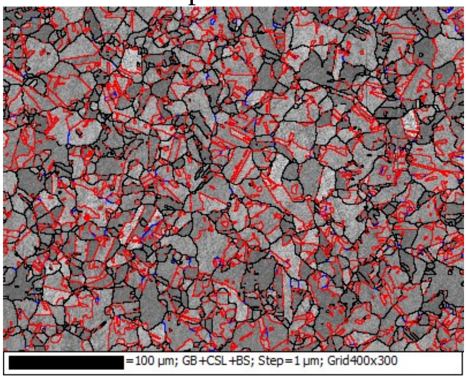


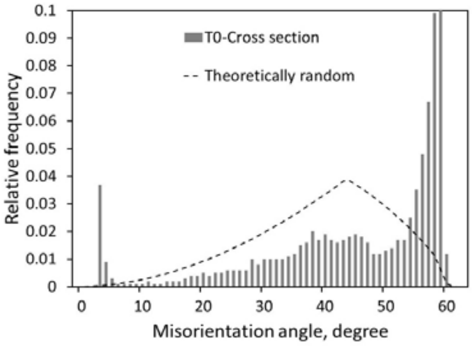
TWIP steel

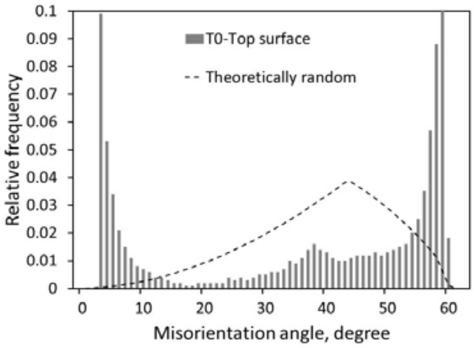
T0 Cross-section (also denoted as Centre)

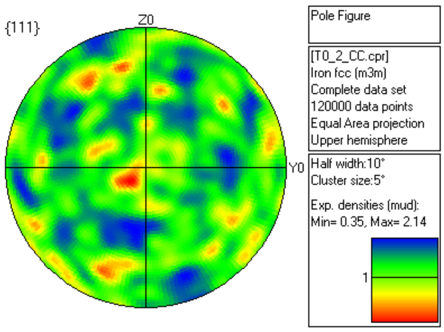


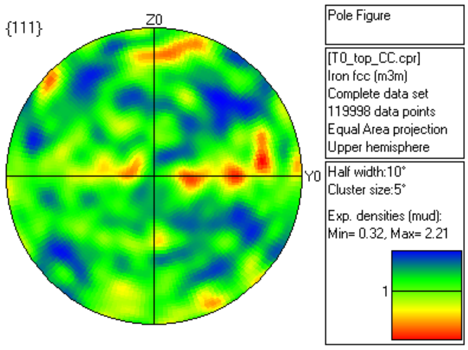
T0 Top surface











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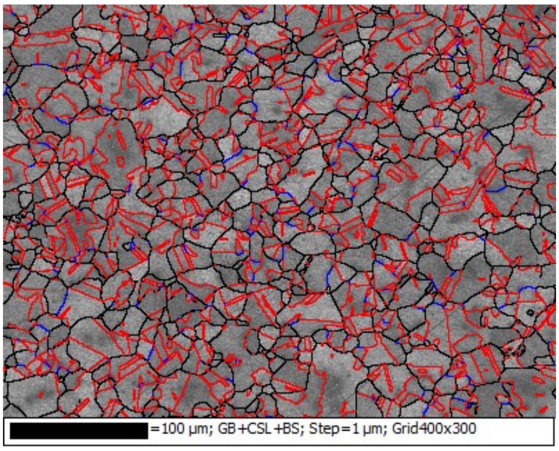
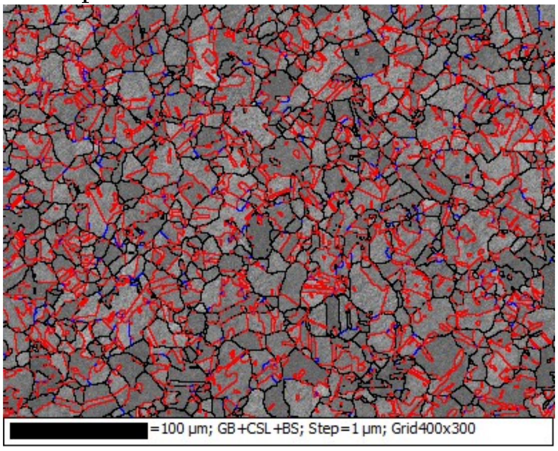
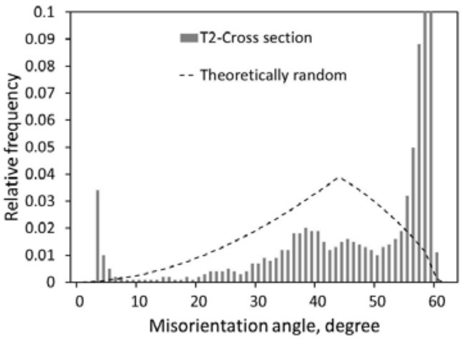
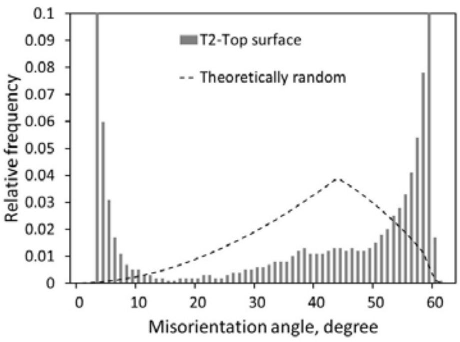
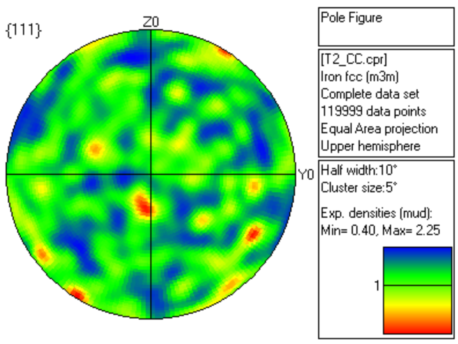


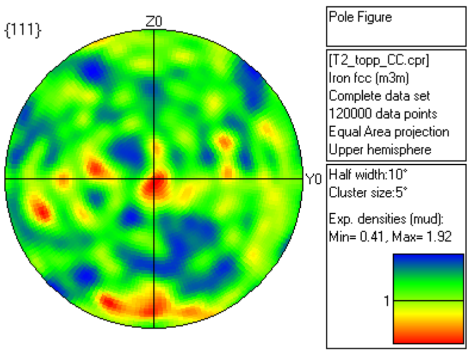
T2 Top surface



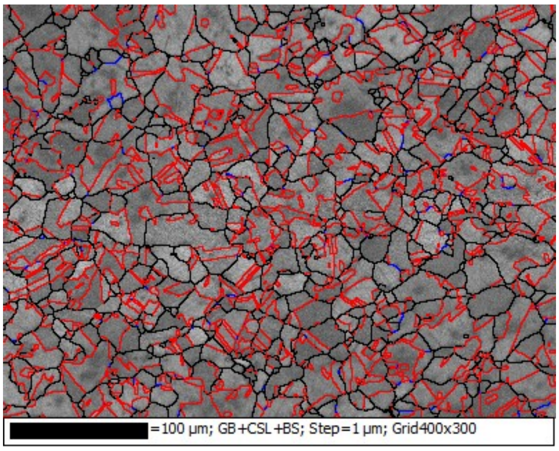




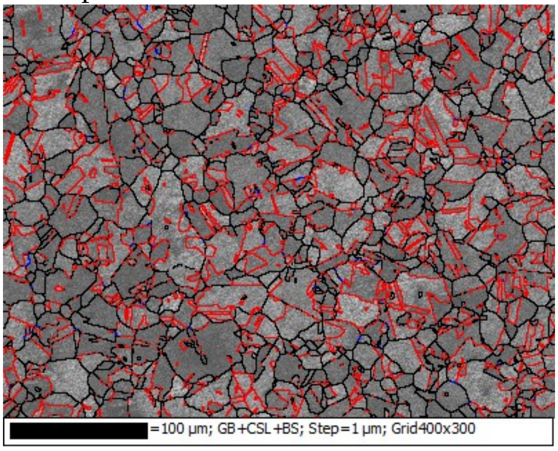


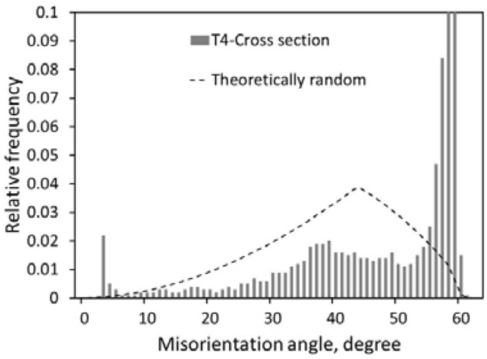


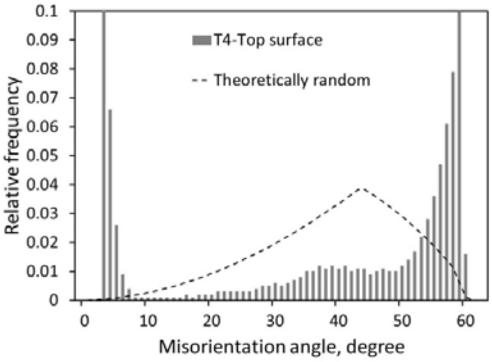
T4 Centre

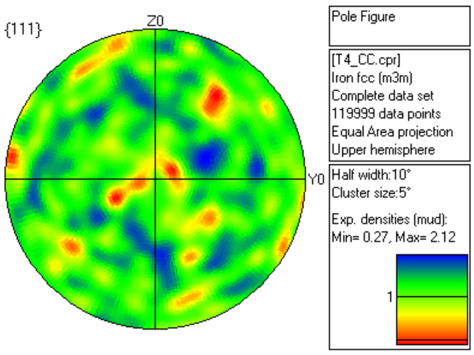


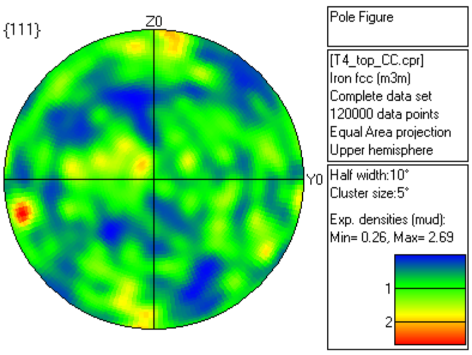
T4 Top surface



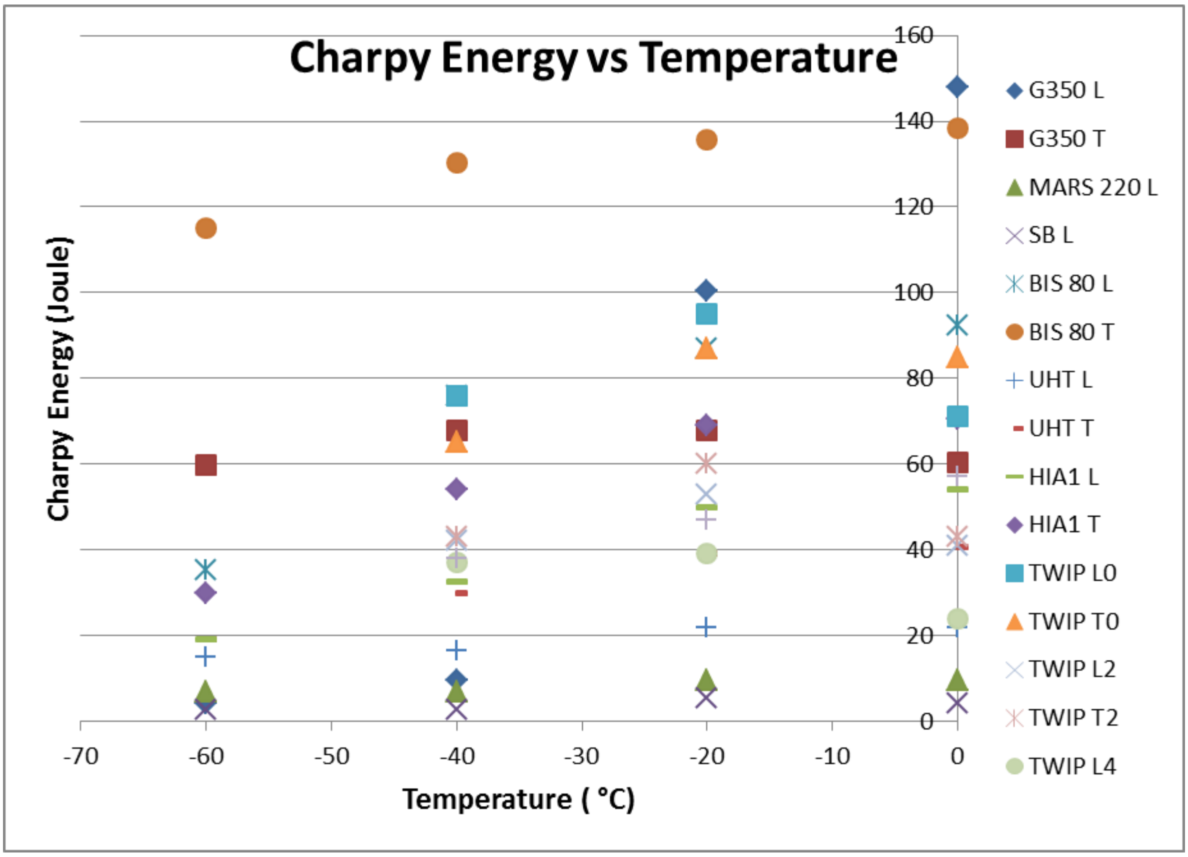








Appendix E: Charpy Energy for All Materials



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Armour, Bulge testing, Blast damage, Metallurgical failure

19. ABSTRACT
It can sometimes be difficult to determine whether vehicles damaged by blast loading are repairable in theatre or so significantly damaged that the hulls must be scrapped. The primary purpose of this investigation is to provide basic metallurgical data to assist in determining the criteria of failure. On top of this, it may be possible that blast loading may actually improve the performance of vehicles by work hardening of the hull and it might be possible to use controlled blasting as a technique to improve blast resistance

Repeated blast test results (up to 7 times) of candidate armour materials showed that the greatest deformation occurred during the first blast and subsequent blasts showed less evidence of deformation. This demonstrates that the steel experienced a significant increase of work hardening after the first blast, at which stage the steels reached a saturated level. Despite repeated blasting, there was little evidence of cracking in the armour steels. Crack-starter explosion bulge testing of the armour steels at -18 °C demonstrated that the steels have adequate toughness in the as-welded condition. This suggests that blasting is not detrimental to the subsequent blast performance of armour.

The work also suggests that appropriate blasting may have a work hardening effect that may be used to increase blast resistance of steels. To test this, the 'pre-blast' concept test program includes hardening of materials by sheet charge blast loading and subsequent

testing of steels by multiple explosion bulge testing. Steels investigated include TWIP steels, a wear plate and armour steels with hardness 450 HV or higher (up to 650 HV). In general, the improvement in deformation resistance is associated with increases in hardness combined with reductions in microstructural grain size.

In practical terms, this work demonstrates that vehicles subjected to blast damage in theatre should not be condemned on the sole assumption that metallurgical damage has occurred to the armour material. Significant savings in cost of repair to blast damaged vehicles are achievable and vehicle availability should be increased considerably.